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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among the papers to appear in forthcoming issues of the *Journal* are the following:

Cyclic calcareous sedimentation as an index of climatic variations in the past. By Werner D. Brückner.

Differentiation of the lower and the upper till along the north shore of Lake Erie. By A. Dreimanis and G. H. Reavely.

Stylolite development post-dates rock induration. By H. V. Dunnington.

Some transverse stylolites. By J. Keith Rigby.

Stylolites and oil migration. By B. M. Shaub.

Shell accumulations in underwater sediments and their relation to the thickness of the traction zone. By Maurice C. Powers and Blair Kinsman.

Petrology and sedimentation of Upper Chester sandstones. By Raymond Siever.

Facies indicators in the Upper Pennsylvanian of Seminole County, Oklahoma. By William F. Tanner.

The sediments of Lakes Florence and Lucy, Central Florida. By W. H. Twenhofel.

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FIGS. 1–8, SEPTEMBER, 1953

THE SIGNIFICANCE OF EVAPORITES[1]

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Northwestern University, Evanston, Ill.

ABSTRACT

Interpretation of the lithologic and paleontologic associations of which evaporites form a part makes possible classification and mapping of the environments involved in evaporite occurrence. Consideration of stratigraphic sequences containing evaporites leads to recognition of a major cycle made up of successive environmental conditions from normal marine, through stages of increasing salinity, to evaporitic conditions. Analysis of the relationship between evaporite occurrences and the elements of the tectonic framework suggests a classification into intra-basinal and basin-margin occurrences. Further classification is based on the nature of the sill responsible for restriction of the evaporitic environment.

INTRODUCTION

Many workers have contributed to our understanding of evaporites, their physico-chemical attributes, and their environmental interpretation. Krumbein (1951), in a recent paper in this journal, has reviewed these findings and has investigated the areal and stratigraphic distribution of evaporites in the United States. In the course of these latter studies Krumbein has shown that evaporites are common in red-bed associations with either quartzose or subgraywacke sands and silts, and in marine associations with carbonates and shales. These evaporites of predominantly marine associations are further shown to be the more significant, volumetrically, and to reach their greatest persistence and volume amid conditions suggesting deposition in active intracratonic basins. The present paper is designed to explore further among the problems of the basin evaporites, their vertical and lateral associations, their tectonic and environmental implications, and their classification.

In the following paragraphs four examples of evaporite occurrence are presented in an attempt to exhibit the nature of the tectono-environmental complex responsible for evaporite accumulation and the succession of paleogeographic conditions which appear to follow one another in typical depositional cycles involving basin evaporites.

[1] Paper presented as part of the symposium on "Paleoecology of shale and evaporite deposition," St. Louis meeting of S.E.P.M., April 26, 1951. Research supported by funds from the Graduate School, Northwestern University.

ENVIRONMENTAL CLASSIFICATION EMPLOYED

The accompanying maps (figs. 1–4) are intended to be paleogeographic. That is, they purport to show the areal distribution of certain conditions during selected moments of geologic time, rather than syntheses of long spans of time. The map patterns attempt to illustrate the distribution of specific environments which are interpreted from the lithologic and biologic record. Such environments have been previously identified and investigated in the West Texas area by Lang (1937), Clifton (1944), and others. The writer's usage is a modification of these previous environmental classifications.

Brackish and Terrestrial Environments

Although they are not an essential part of the environmental complex involving evaporite deposition, brackish water sediments and deposits formed by streams, swamps, lakes, and wind action are of common occurrence marginal to areas of evaporite accumulation. Such

deposits, formed around the edges of evaporite basins, are typically red beds, dominated by clastics in the sand, silt, and clay sizes. Thin and impersistent evaporites are common. As Lang (1937) has pointed out, under conditions of extreme aridity highly saline waters may approach close to the strand line and saline deposits may be separated from terrestrial beds by a narrow belt of sediments formed in a marginal brackish-water zone. Insignificant lateral shifts may bring evaporitic, brackish, or terrestrial sediments to a depositional site in the marginal zone. Fossils are rare but may include land tetrapods, plant remains, fresh and brackish water pelecypods, gastropods, and ostracods. No attempt is made to distinguish among the variety of brackish and terrestrial environments concerned on the accompanying maps.

Normal Marine Environments

Areas mapped as "normal marine" are those in which the significant rock types are fossiliferous and fossil-fragmental limestones and their dolomitized equivalents. Common textures in primary carbonates range from fine "bioclastic" material in the silt sizes to coarse fragmental debris. Dolomitized carbonates are chiefly fine to medium saccharoidal with numerous vugs representing dissolved fossil fragments. Colors are typically light. Chert, where present, appears to be secondary and occurs in nodules or disconnected lenses. Fossils cover the entire range from foraminifera to arthropods and are dominated by benthonic forms.

Such deposits are interpreted to represent epicontinental marine areas of normal salinity with unrestricted circulation and unimpeded communication with the open ocean. Textures, structures, and fossils suggest moderate depths within the littoral and neritic zones. The abundance of carbonates and the lack of organic carbon and hydrocarbons indicate conditions of high pH and high oxidation potentials (Krumbein and Garrels, 1952) in the depositional and diagenetic environments.

Clifton (1944) has recognized beds containing normal marine faunas occupying a geographic position between evaporites and brackish water sediments. He has termed these "pseudomarine" and has interpreted them as being the result of dilution of the margin of a saline sea by meteoric water from a nearby land area (see figs. 6 and 8). Such conditions appear to be reproduced near the landward margins of a number of evaporite basins but have not been separately identified on the accompanying maps.

Reefs form a special case in the normal marine environment. Where they occur in association with evaporites their generalized position is identified on the accompanying maps by black, banana-shaped, patterns.

Euxinic Environments

Euxinic environments, as here mapped, are those characterized by accumulation of black shales and limestones rich in organic matter. Sands may be present but they are of external derivation and have little bearing on environmental interpretation. The shales range from fissile paper shales to massive mudstones and bear varying percentages of carbonate. The limestones are dense in texture, commonly nodular and argillaceous. Little evidence can be found for extensive dolomitization. Fossils are very rare, and, where present, appear to be confined to planktonic and nektonic types.

It is assumed that euxinic environments represent the restriction of marine waters under conditions which inhibit circulation but with sufficient inflow of open sea and meteoric waters to maintain salinity at or somewhat below normal levels. Such circumstances lead to incomplete overturn and oxygenation with progressive stagnation and increasing toxicity of the bottom waters. No normal benthonic fauna is capable of surviving to add its shells and fragments to the sedimentary record and the organic debris generated by plankton accumu-

lates on the bottom in the absence of scavengers and aerobic bacteria.

Penesaline Environments

Environments intermediate between normal marine and saline are termed penesaline, a modification of Lang's (1937) usage. The penesaline environment is characterized by deposition of evaporitic carbonates, chiefly primary dolomite, interbedded with anhydrite. The latter, commonly light pink, light gray, or white, offers no problem in identification. The evaporitic carbonates, on the other hand, are the subject of continuing debate. In the writer's view the following types of evaporitic carbonates are formed in the penesaline environment:

1. Dense, unfossiliferous strata, light in color, finely laminated, and more commonly dolomite than limestone. Anhydrite may be present as isolated blebs and stringers. These beds are interpreted as primary precipitates by physicochemical action without the intervention of organic agencies.

2. A matrix of dense or finely crystalline carbonates with isolated rhombic dolomite crystals or segregations of crystals. The rhombic crystals are interpreted as replacements of the matrix during deposition or upon diagenesis.

3. Saccharoidal dolomites made up of well-sorted dolomite rhombs with marked intercrystalline porosity and lacking significant intergrowth of crystals. Crossbedding and other structures typical of "sand," are common. Sugary dolomites of this type are believed to represent the reworking of dolomite rhombs formed as in type (2) with the fine matrix removed by bottom currents.

4. Oolitic carbonates interpreted to be the result of agitation of sediments by wave-generated currents in carbonate-saturated waters.

Penesaline sediments imply the maintenance of conditions characterized by concentrations of marine salts sufficient to be toxic to normal marine life and yet insufficient to permit the precipitation of chlorides. Such conditions are interpreted as the result of restriction of a marine basin in an arid climatic regime. Persistence of penesaline conditions requires a nice balance between inflow of normal sea water and evaporation. The common occurrence of penesaline sediments in intracratonic basin accumulations is testimony to the frequency and duration of this delicate equilibrium.

Saline Environments

The environment here termed saline is characterized by major accumulations of halite and anhydrite, with only minor interbeds of carbonate, if any. The precise boundary between penesaline and saline environments is difficult to define but experience suggests that there is a useful distinction between areas in which sulfates and carbonates are intimately interbedded and areas dominated by sulfate-chloride deposition in the absence of carbonates.

As in the case of the penesaline, the occurrence of saline beds in basinal deposits implies the restriction of marine waters under arid conditions with continued inflow of normally saline water to preserve the required geochemical equilibrium.

Supersaline Environments

A special case, the supersaline environment, is invoked for those exceptional deposits characterized by abnormal concentrations of potash salts. In North America this special environment seems to be represented only in the Salado evaporite of the West Texas-New Mexico Permian and the Elk Point group of the southern Saskatchewan Middle Devonian. It is generally assumed that supersaline deposits represent the end member produced by restriction and evaporation of marine water. The influence of secondary enrichment in the formation of potash-rich beds is not to be overlooked, but it seems probable that the areas and zones of possible secondary enrichment were also sites of high primary potash content.

PALEOGEOGRAPHIC MAPS

The areal distribution of the environments discussed above at specific points in geologic time are shown on the accompanying maps. Boundaries between environments are shown as sharp lines, when, in fact, such boundaries are gradational. The bounding lines are intended to designate areas of predominate environmental tendencies and are not precise limits based on quantitative data.

In addition to the environments the maps bear a special pattern of fine dots to indicate those areas in which rocks of the time unit concerned have been stripped by subsequent erosion. Such areas are thus differentiated from other areas of non-occurrence believed to represent areas of nondeposition.

Permian of West Texas-New Mexico

Long study of the Permian basin area, in recent years by King (1942, 1948), Adams (1944), Lang (1937), Hills (1942), Roth (1942), and others has made this a classical area for the study of evaporites. Figure 1 illustrates the distribution of environments during parts of each of the four epochs of Permian time.

Wolfcampian.—The Wolfcampian map indicates humid restricted conditions leading to the deposition of black limestones and shales in the Delaware and Midland basins. Much of the shelf area surrounding the basins was occupied by open unrestricted seas in which normal marine limestones (Hueco and equivalents) were deposited. Terrestrial red beds (Wichita group) were forming to the north of the shelf sea and other nonmarine sediments accumulated to the south along the flank of the Marathon folded belt.

Leonardian.—A further differentiation of environments is noted in Leonardian time. Continued humid restriction of the Delaware and Midland basins is marked by the euxinic Bone Spring limestone. In this epoch one of the factors responsible for restriction may be found in the persistent reef trends occupying the hinge lines separating the basins from their enclosing shelves. Normal marine conditions (San Andreas and equivalents) continue to prevail along the southern margin of the shelf area. To the north, where the sea has transgressed over Wolfcampian terrestrial beds, inadequate circulation from the open marine area to the south is the apparent cause of gypsum and anhydrite deposition in the Pease River and equivalent units.

Guadalupian.—Significant alterations in the pattern of tectonics and environment are introduced in the Guadalupian. Contraction of the sea exposes large areas of the northern shelf to terrestrial conditions. The shelfward margin of the the sea remains the site of saline environments but the saline area has shifted to the south with the receding sea. Anhydrite deposition associated with the Whitehorse group is carried into the area of the Midland basin and its previously normal marine margins, overwhelming and burying the reef trends. It would appear that tectonic activity of the Midland basin has ceased, ending its environmental differentiation from the adjacent shelf. The Delaware basin, on the other hand, gives evidence of continued negative tendencies under open circulation conditions which lead to the deposition of the sandstones and normal marine limestones of the Delaware Mountain group. A nearly continuous barrier reef trend around the margins of the Delaware basin appears responsible for the separation of basinal sediments from the Carlsbad and equivalent marine limestones of the immediate back-reef area.

Ochoan.—During the final epoch of the Permian normal marine conditions were confined to the limited area of the Marfa basin near the southwest margin of the province here considered. The remainder of the area bears a record of extreme restriction which may be, at least partially, attributed to a barrier of reefs in the Hovey channel at the head of the Marfa basin. To the north, the area which had previously exhibited a variety of tectonic and environmental differentiation is blanketed by the saline and supersaline

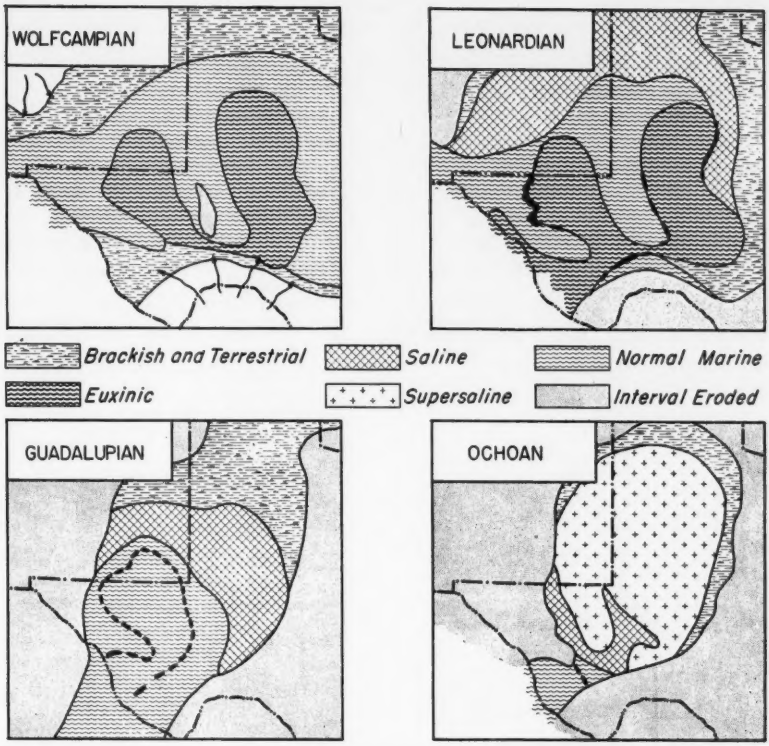

FIG. 1.—Paleogeographic distribution of Permian evaporite and related environments in the West Texas-New Mexico area. The black blobs represent the inferred positions of reef trends.

deposits of the Salado and Rustler formations which sweep impartially across the Delaware basin, its reef-girt margins, and the previously involved area of the Midland basin.

The close of Permian deposition is marked by the widespread distribution of terrestrial red beds (Dewey Lake) which appear to represent sedimentation on an uninterrupted shelf prevailing over the entire area.

Summary of West Texas-New Mexico Permian pattern.—A review of the Permian basin pattern of successive environmental and tectonic influences on sedimentation suggests the following sequence:

1. Establishment of a fully differentiated tectonic framework in the earliest Permian, with restricted euxinic environments in the basins, normal marine conditions on the surrounding shelves, and brackish and terrestrial deposition at the margin of the sea.

2. Continuation of the initial pattern into the Leonardian, but with the establishment of saline environments at the distal margins of the shelf sea.

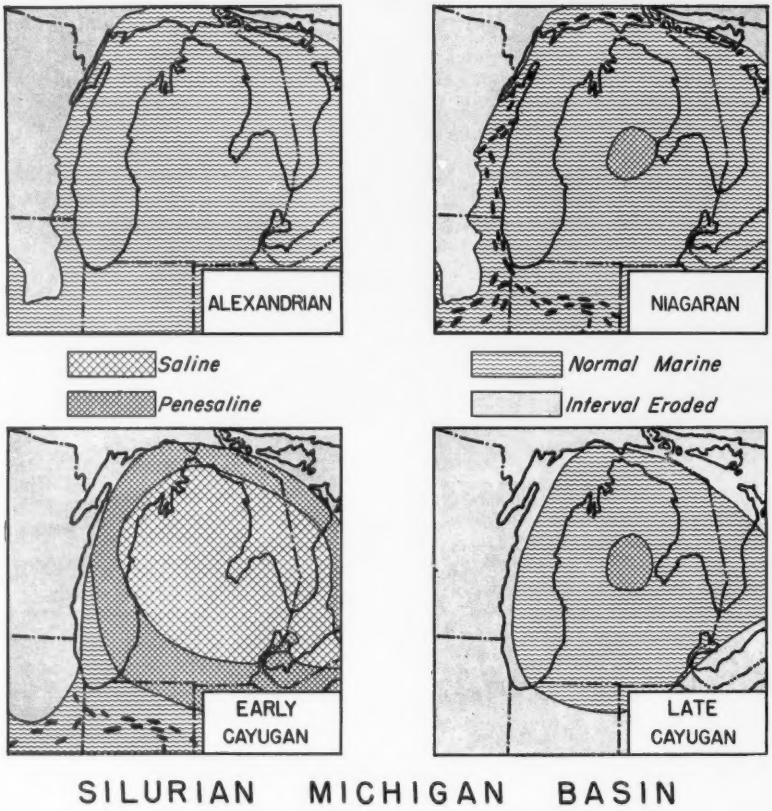

FIG. 2.—Paleogeographic distribution of Silurian evaporite and related environments in the Michigan Basin area.

3. Southward retreat of the sea (Guadalupian) accompanied by decrease in negative tendency of the Midland basin and its addition to the area of evaporite deposition.

4. Formation of a single markedly restricted evaporate basin without differentiation of previous shelves and basins.

5. Tectonic stabilization of the entire area and deposition of a veneer of terrestrial red beds.

Silurian of Michigan Basin

The Silurian of the Michigan basin area (fig. 2) has long been a familiar example of evaporite occurrence. Latter-day investigations by Cohee (1948), Landes (1945), Lowenstam (1950), and others have provided data for comparing the Michigan basin evaporites with those of West Texas-New Mexico and other areas.

Alexandrian.—During Early Silurian time the area was covered by a normal

marine sea from which was deposited a relatively thin and fairly uniform sheet of sediment, without apparent tectonic distinction of the Michigan basin.

Niagaran.—Normal marine environments continued to prevail over most of the area in Middle Silurian time, but isopach studies suggest a tectonic differentiation of the basin from the surrounding stable shelf areas. To the south of the basin, the stratigraphic record of the Middle Silurian indicates an abundance of randomly oriented reefs on the shelf area of northern Indiana and Illinois. Equivalent reef masses take on an appearance of a circum-basinal trend in eastern Wisconsin and the Upper Peninsula of Michigan. Inasmuch as the apparent reef trend is confined between the erosional limits of Niagaran rocks on the west and north and Lakes Michigan and Huron on the east and south, the validity of any such trend is difficult to establish. It is possible that a scattering of reefs was once present in the areas of Wisconsin and the Upper Peninsula from which Niagaran rocks have been stripped but it is also probable that the reefs ended more or less abruptly near the margin of the basin. Deep wells suggest penesaline deposition and an absence of reefs in the central area of the basin.

Early Cayugan.—The beginning of Late Silurian time witnessed the maximum tectonic and environmental differentiation of the area. Paleogeographic reconstruction is impeded by a general lack of accurate time-rock correlation across the belts of high rate of facies shift from normal marine to saline. An approximation of the regional picture may be drawn, but the details will vary with differing interpretations of the complex correlation problems.

The details of closely-studied Silurian reefs in Illinois and Indiana and their relationships with enclosing strata and with the overlying Lower Devonian strongly suggest the continuity of reef growth from Niagaran through much of Late Silurian time. It also appears probable that similar reefs were continuous around much of the Michigan basin in this epoch. Within this reef barrier a ring of penesaline dolomites and anhydrites is laterally succeeded by the thick saline beds of the Salina group as the more tectonically negative center of the basin is approached.

Late Cayugan.—The close of Silurian sedimentation is marked by cessation of negative tendencies in the basin, the breakdown of environmental differentiation of the basin and its margins, and the spread of normal marine deposits (Bass Island) over most of the previously saline area. A remnant of penesaline conditions is represented by minor anhydrites near the center of the former basin.

Summary of Michigan Basin Silurian.—1. Normal marine environments over a relatively undifferentiated shelf.

2. Inception of definite negative tendencies in the basin; development of a peripheral reef complex; establishment of penesaline environments in the basin.

3. Maximum negativism of the basin; penesaline and saline environments at least partially effected by reef-imposed restrictions of the basin.

4. Stabilization of basin and renewed spread of open-circulation marine waters across previously differentiated areas.

Upper Devonian of Montana-Alberta

Detailed surface investigations and an expanded program of deeper drilling in northern Montana and southern Alberta have produced data which may be analyzed in terms of the tectonic and environmental influences on Upper Devonian evaporite deposition in the area. The accompanying maps (fig. 3) are generalizations based on publications by Sloss and Laird (1947), Link (1949), Layer *et al.* (1950), DeWit and McLaren (1950), Andrichuk (1951) and Baillie (1953).

Early Senecan.—Near the opening of Upper Devonian time the area here considered became tectonically stable, following several episodes of marked tectonic differentiation in the Middle De-

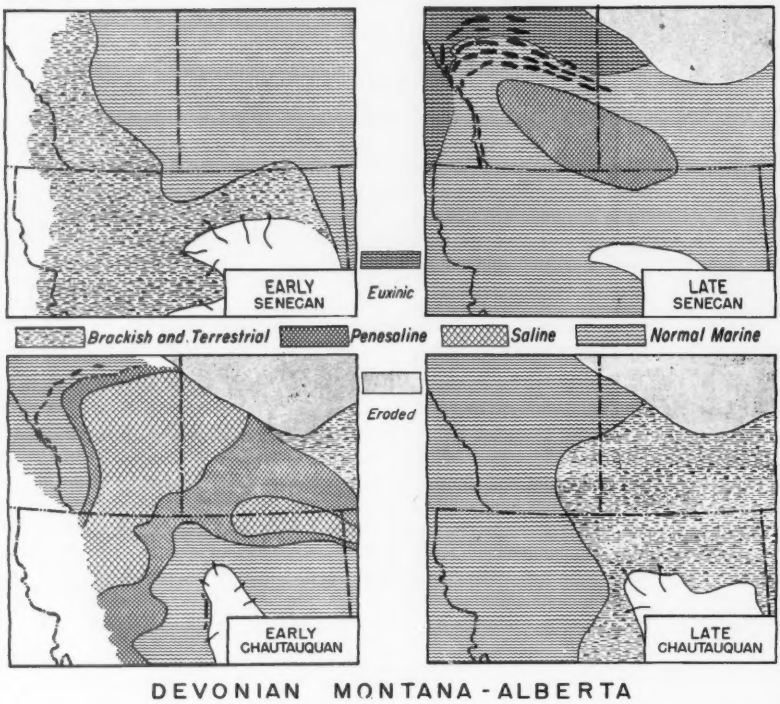

FIG. 3.—Paleogeographic distribution of Upper Devonian evaporite and related environments in the Montana-Alberta-Saskatchewan area.

vonian. A relatively uniform sheet of sediments was laid over the area, with non-marine or brackish environments (Maywood, and part of Ghost River formations) prevailing to the south and west while open marine conditions (lower Beaverhill Lake, Point Wilkins, etc.) occupied the broad area east of central Alberta and north of the international boundary.

Late Senecan.—Renewed tectonic differentiation of the area is evident in the deposits of later Senecan time. Subsiding basins with environments ranging from normal marine to euxinic became active in central and south central Alberta and in the Cordilleran trend of southwestern Alberta and adjoining areas of British Columbia (Duvernay, Ireton, Perdrix, etc.). South and east of these basins more stable tectonic states were the rule in southern Alberta and Saskatchewan and in northern Montana. Persistent reef trends (Leduc, upper Fairholme) appear to have developed around the margin of the southern shelf area and the hinges bounding the basins. The shelf sea south and east of the reef trends was predominantly open-circulation in type (limestone member of Jefferson, Cooking Lake, etc.); with local restrictions evidenced by numerous evaporite cycles in southeastern Alberta and southern Saskatchewan. The majority of these cycles reached

penesaline environments, but locally, as in the Davidson area of Saskatchewan, fully saline conditions were achieved temporarily.

Early Chautauquan.—In the succeeding stage of Late Devonian time the area of northern Montana and southern Alberta witnessed a marked expansion of penesaline and saline environments. There were deposited widespread evaporitic dolomites and anhydrite (Potlatch) over the inner margins of the previously established reef trend and over much of the reef-enclosed shelf.

Normal marine conditions prevailed over the outer margins of the old reef trend and in peripheral areas to the west and north (Lower Wabamun, Lower Palliser, etc.). In the southeastern quarter of the map area the depositional record suggests an approach toward normal marine conditions around the border of an emergent area in central Montana and on the Wyoming shelf. The latter normal marine area possibly represents dilution of the saline waters by run-off from the adjoining land—a pseudo-marine environment.

Late Chautauquan.—Near the close of the Devonian the entire area became tectonically stable and was covered by a relatively thin and uniform sheet of sediment. Environments ranged from normal marine (upper Three Forks, uppermost Wabaman, upper Palliser, etc.) on the west and north, to non-marine and brackish around the land area on the east and south (Lyleton).

Summary of Montana-Alberta Upper Devonian.—1. An undifferentiated stable tectonic framework at the opening of Late Devonian time. Area divided between brackish-terrestrial and normal marine environments.

2. Differentiation of the area into a central shelf bounded by subsiding basins on the north and west. Development of reef trends at the shelf margins, an alternation of normal marine and euxinic conditions in the basins, and penesaline to saline environments on the shelf in response to (reef-imposed?) restricted circulation.

3. Expansion of restricted conditions with evaporite deposition overwhelming the inner limits of the reef trend and spreading over much of the shelf area.

4. Return to uniformly stable conditions at the end of the Devonian with normal marine conditions predominating.

Mississippian of Williston Basin

Mississippian strata of the Williston basin area in Montana and North Dakota provide another well-documented example of evaporite relationships. Figure 4 illustrates the distribution of environments over this area during parts of Mississippian time.

Kinderhookian.—At the opening of the Mississippian, the area was relatively stable and there was little differentiation of the Williston basin area from the surrounding shelves. This tectonic homogeneity is indicated by the uniform blanket of sediments of earliest Kinderhookian age and represents a continuation of latest Devonian stability as discussed in the preceding paragraphs. Euxinic environments appear to have prevailed over much of the area as indicated by widespread black shales and limestones (Exshaw, lower Banff, lower Lodgepole). Normal marine conditions extended around the western margin of the emergent Wyoming shelf, while non-marine and brackish environments were the rule around the southeastern margin of the sea (Englewood).

Osagian.—The deposits of early Middle Mississippian time constitute a great sheet of limestones (Mission Canyon, Rundle, etc.) which extended far beyond the limits of the area here considered. These limestones are significantly thicker in the area straddling the Montana-North Dakota border where evaporitic dolomites and minor anhydrites occur. The isopach and facies patterns clearly indicate the initiation of tectonic and environmental differentiation of the Williston basin from the surrounding shelf. Except for the axial area of the Williston basin and the euxinic (Milligen) Idaho

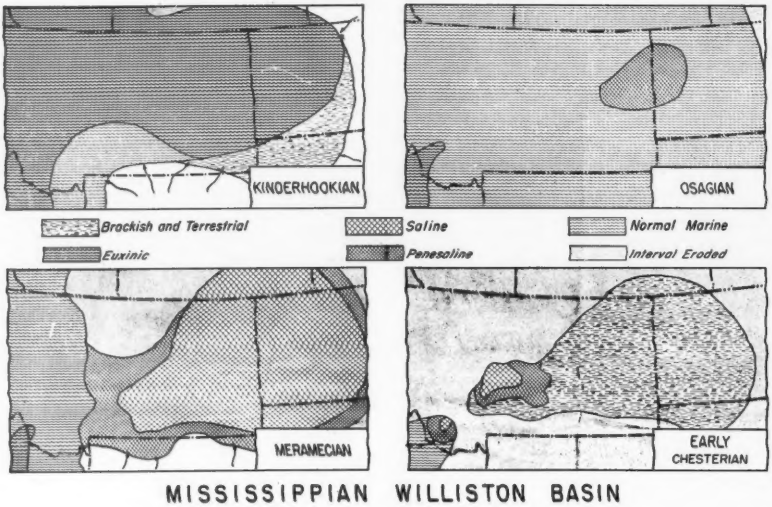

FIG. 4.—Paleogeographic distribution of Mississippian evaporite and related environments in the Williston Basin area.

basin at the southwest, normal marine conditions predominate everywhere.

Meramecian.—In later Middle Mississippian time the area attained a maximum of tectonic and environmental differentiation. Thickness figures show the degree of differential subsidence of the Williston basin, and, the thick anhydrites and minor salt deposits (Charles) indicate the prevalence of saline conditions. The basinal evaporites may be traced laterally into penesaline and normal marine sediments to the west (uppermost Mission Canyon, "outcrop Charles," upper Rundle), no barrier between the saline and normal marine seas being apparent. Continued subsidence of the Idaho basin under mixed euxinic and normal marine environments is evidenced by the thick black limestones and fossiliferous limestones of the Brazer.

Early Chesterian.—Although the pattern of Late Mississippian sedimentation is obscured by extensive erosion, certain relationships are fairly clear. Early Chesterian clastics of the Kibbey formation maintain relatively constant thicknesses over the area, suggesting a return to tectonic stability. The Kibbey red beds were deposited under non-marine or brackish environments with evaporitic deposits confined to local basins at the western end of the formerly negative axis. Limestones high in the Brazer suggest the development of normal marine environments and the end of restriction of the Idaho basin.

Summary of Williston basin Mississippian.—1. Spread of euxinic, brackish, and terrestrial environments over an essentially stable and undifferentiated shelf.

2. Initiation of the Mississippian Williston basin with restricted penesaline environments at the basin center, surrounded by widespread normal marine conditions.

3. Climax of negative tendency of Williston basin with concurrent restriction and saline deposition.

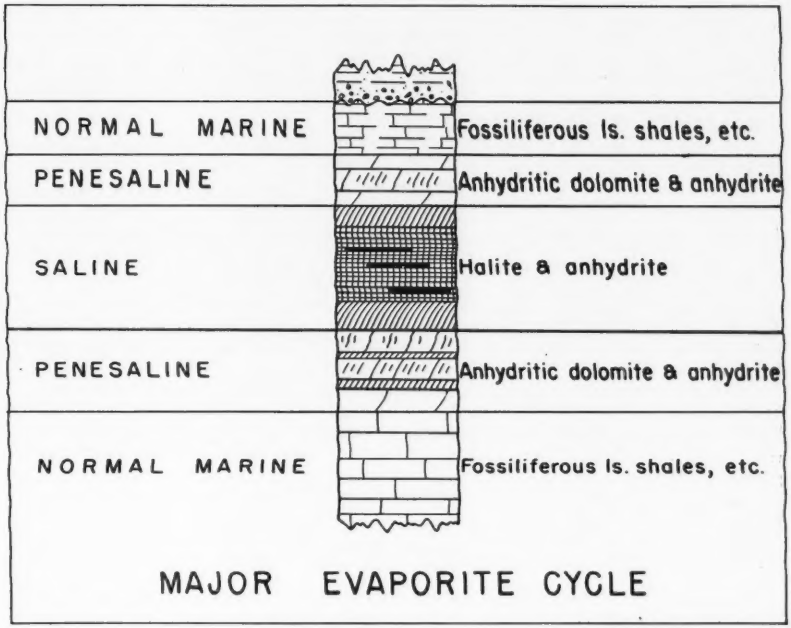

FIG. 5.—Diagrammatic representation of a major evaporite cycle.

4. General tectonic stabilization of much of area except for minor local evaporite basins.

MAJOR EVAPORITE CYCLES

Analysis of the four examples discussed in preceding paragraphs, along with consideration of other major evaporite accumulations, suggests that in each case a definite and almost predictable sequence of tectonic and related environmental conditions is involved. Figure 5 is a diagrammatic interpretation of the major cycle of which each important evaporite accumulation seems to be a part.

The pattern as presented is greatly oversimplified and obscures the fact that each stage in the major cycle is compounded of many minor cycles while each of these may have individual characteristics flavored by clastic admixtures, the nature of contributing organisms, idiosyncrasies of climate, and so forth. Such minor cycles have been described by Lang (1937, 1950), Woolnough (1937), Roth (1942), Hills, (1942), Adams, (1944), Laudon, *et al.* (1949), Andrichuk (1951), and others.

It is apparent that penesaline deposits may be found as part of a minor cycle in a dominantly normal marine succession, and normal marine beds are not unknown amid a thick section of saline deposits. In each case, however, analysis shows that one phase or member of the minor cycle dominates the others, even though the whole spectrum from normal marine to saline may be present. The stages discussed here and illustrated on the accompanying diagram are identified by the dominant environmental stage represented.

Identification of dominant environment is most difficult where isolation of the penesaline is involved since minor cycles are commonly well developed and include both saline and normal marine members. Saline and normal marine stages of the major cycle, on the other hand may involve fusion of a number of minor cycles, with the end-member stages present without interruption through tens or hundreds of feet of section.

The ideal major cycle is initiated in a section dominated by fossiliferous limestones indicative of open circulation and normal marine salinities. This normal marine section is superseded by interbedded dense dolomites and thin anhydrites lacking fossils of indigenous benthonic origin. These beds represent the partially restricted penesaline environment and are followed in upward succession by massive anhydrite and halite beds of the markedly restricted saline environment. In rare instances extreme restriction prevails for a sufficient length of time to account for the development of significant supersaline deposits.

The upward succession from normal marine to saline (or supersaline) may be thought of as the *advancing restricted hemicycle*. In the infrequently encountered perfect case the advancing hemicycle is superseded by the *relaxing restricted hemicycle* in which saline beds grade upward into penesaline and finally back to normal marine strata, representing a slackening of the grip of restricting conditions on the depositional environment.

If a tectonic interpretation of the stages of the evaporite cycle is made by reference to facies and isopach patterns it may be shown that the basinal subsidence of the province concerned tends to vary directly as the degree of environmental restriction. Thus, the evaporite cycle is both an environmental and tectonic phenomenon. In the general case, the initial normal marine phase is expressed by a sheet of limestone which gives little evidence of tectonic differentiation of the area covered. The penesaline phase is normally characterized by marked isopach rates of change which reflect the differentiation into shelves and basins with hinge lines and platforms. These tendencies are increasingly manifest in the saline stage, and supersaline conditions appear to have been attained only in those areas of extreme disparity of tectonic states.

In the proposed interpretation the advancing hemicycle is seen as a progression toward higher and higher states of tectonic instability and differentiation, whereas the relaxing hemicycle follows the reverse course back toward stability and the uniform shelf. The record of evaporite cycles suggests that the component hemicycles are of unequal duration, with the advancing half being represented by thicker deposits than the relaxing portion. Furthermore, with the return to stability at the close of a cycle the area involved is commonly exposed to erosion which may serve to strip the thin record of the relaxing hemicycle and cause the initial deposits of the succeeding cycle to lie disconformably on a surface cut on saline beds. The latter situation is, perhaps, the most frequently observed relationship of evaporite cycles.

EVAPORITE—REEF RELATIONSHIPS

The common association of reef complexes and major evaporites is so well documented in the literature and in the stratigraphic record that reef exploration is often guided by the distribution of evaporites. Many workers have attempted to resolve the enigma of a maximum concentration of organisms operating side-by-side with saline concentrations which tend to exclude all but a few animals or plants. Lang (1937) has applied the term "vitasaline" to the reef zone and has suggested that it is intermediate between normal and penesaline phases of marine deposition, with an abnormal concentration of marine salts contributing to easy precipitation by organic agencies. Others have indicated

that reef growth precedes evaporitic conditions and is terminated by increased salinity, with no concurrent existence of both reefs and saline waters.

The present writer is not inclined to the belief that either of these views will fit the data on the majority of evaporite-reef occurrences. There is little evidence from modern reefs or from the many instances of ancient reefs unrelated to evaporites that hypersalinity or excessive calcium carbonate concentrations are significant factors in reef localization. On the other hand, subsurface investigations often suggest that evaporites may be traced laterally along approximate time surfaces into reef structures.

Regardless of the ultimate causes, an interrelationship is apparent. Most of the reefs associated with the evaporites are linear complexes of the barrier type, and most seem to be developed along the tectonic hinges separating basins and shelves at the times of most explicit differentiation of such elements.

EVAPORITE—EUXINIC RELATIONSHIPS

Evaporites are commonly associated with black shales and limestones attributed to an euxinic environment. The association may be areal, with euxinic beds on one side of a reef or other barrier and evaporites on the other (Leonardian of West Texas-New Mexico, Late Senecan of Alberta), or vertically interbedded (as in the Paradox formation of the Utah Pennsylvanian). The first case offers no great problem of interpretation. Both types of deposit represent restricted environments with the difference determined by climate and the relative rates of evaporation, and inflow of meteoric or normal sea water (Woolnough, 1937).

Krumbein and Garrels (1952) have shown that intimate interbedding of euxinic and evaporite deposits requires an alternation of extremes in Eh-pH relationships that can not be easily accounted for by current interpretations. The paper cited suggests that under special circumstances negative redox potentials and the preservation of organic matter as black mud may prevail below the depositional interface while sulfates and chlorides are precipitated in an oxidizing environment in the waters above.

CLASSIFICATION OF EVAPORITE OCCURRENCES

Review of the evaporite cases presented in previous paragraphs, plus consideration of the many other evaporite occurrences documented by field studies and subsurface data, suggests a related group of tectonic and geographic factors common to all volumetrically significant evaporite deposits. The majority of such deposits may be shown to be related to cratonic basins which were actively subsiding during the times of evaporite accumulation. The most frequently observed type occupies the central area of a basin and passes laterally into terrestrial, brackish, or normal marine beds at the basin margins. Other occurrences occupy the periphery of a basin and grade basinally into normal marine or euxinic deposits.

In each case a restricting agency must have operated during evaporite deposition to account for the continued maintenance of high salinities. It is almost universally accepted that a submerged or partially submerged sill, permitting the inward flow of normally-saline sea water to replace evaporation and inhibiting the outward flow of dense hypersaline waters, is a logical restricting agency. In some instances the nature of the sill may be demonstrated, as where reef trends coincide with the margins of evaporite deposits. In other cases there are evidences of shoaling in linear trends of banked bioclastic debris or sand bars separating evaporites and time-equivalent non-evaporitic strata. In some examples no definite trend of reefs, shoals, bars, or banks can be identified. Instead, there is a relatively broad transitional belt within which marine, penesaline and saline deposits intertongue, apparently in response to shifting topographic features of low relief which reflect shifting wave and current patterns. Such ephemeral fea-

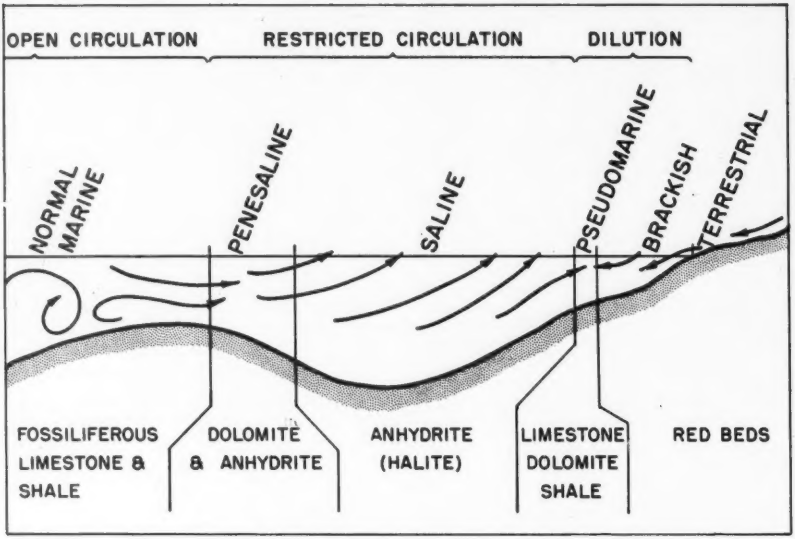

FIG. 6.—Diagrammatic profile showing relationships of topography and environment in tectonically-silled intra-basin evaporite accumulation.

tures would not exist long enough along any one trend to from a recognizable body of rock but would nevertheless operate as a sill-forming mechanism as efficiently as a fixed and stable feature.

In attempting a classification of evaporite occurrences, the writer has arranged the major basinal evaporites noted by Krumbein (1951) according to their position with regard to the basin in which they occur. Within these major groupings further categories are erected according to the nature of the restricting sill. The results of this tentative classification are given in table I.

Intra-basin Evaporites

As the table indicates, the great majority of recognized North American evaporites occur in the central areas of basins which were tectonically negative during evaporite deposition. Analysis of the nature of the restricting mechanisms involved permits subdivision of the intra-basin occurrences. An attempt is made in the following discussion to identify the restricting agency as the topographic result of tectonic differentiation or as a linear trend of reefs. It is clear, however, that all combinations are likely to occur around the periphery of a basin at any instant in time, and that the character of the sill at any point in the margin of a basin may change during the long time span of evaporite accumulation. The tentative classification presented is based on the apparent dominance of one type of sill over another.

Tectonically-silled Intra-basin evaporites.—Figure 6 is a diagrammatic representation of an evaporite basin in which the distribution and maintenance of evaporitic environments results from the nature of the tectonic framework. The hypothetical area diagrammed is characterized by an open-circulation marine basin at the left, separated from a subsiding intracratonic basin by a stable

TABLE I

Area	Age	Formation or Interval	Intra-basin	Evaporites	Basin-margin Evaporites		Remarks
			Tectonically-silled	Reef-enclosed	Back-reef	Topographically-silled	
Gulf Coast	Cretaceous	Ferry Lake, Fredericksburg	X				
Florida	Cretaceous	Comanchean	?				Limits and restricting factors unknown, probably tectonic
Upper Gulf Coast	Jurassic	Buckner	X(?)	?			Limits and restricting factors unknown, possibly some reef involvement
Wyoming—Montana	Jurassic	Gypsum Spring	X			x	
Idaho	Jurassic	Preuss	X				
Utah	Jurassic	Arapien	X				
Midcontinent, Texas Panhandle, central Texas, New Mexico	Permian	Whitehorse, San Andres, Clear Fork, Wichita, Wellington, Chalk Bluff			X	x	
Gulf Coast	Permian	Louann	X(?)				Age disputed, possibly Jurassic
West Texas—New Mexico	Permian	Salado	X	?			Possible involvement of reefs in Hovey channel
Paradox Basin, Utah	Pennsylvanian	Paradox	X	?			Margins not fully explored, reef involvement possible
Williston Basin	Mississippian	Charles	X				
Illinois Basin	Mississippian	St. Louis	X				
Michigan Basin	Mississippian	Michigan	X				
West Virginia	Mississippian	Maccrady	X				
Michigan Basin	Devonian	Detroit River	X	?			Possibly reef enclosed
Alberta—Montana—Saskatchewan	Devonian	Potlatch, Jefferson, Cooking Lake, Beaverhill Lake	x		X		Specific evaporites related to local basins in back-reef area
Manitoba—Saskatchewan—E. Montana—N. Dakota	Devonian	Elk Point	x	X(?)			Margins of basin not fully explored, possible predominance of unaided tectonic influence
Michigan Basin	Silurian	Bass Island	X				
Michigan Basin	Silurian	Salina		X			Margins not fully preserved, continuity of reefs assumed
Iowa	Silurian	Middle (?)	X				
Williston Basin	Ordovician	Red River	X				
Illinois Basin	Ordovician	Joachim	X				

"X"—indicates dominant restricting factor. "x"—indicates minor restricting factor. "?"—indicates questionable restricting factor

element. The submarine topography illustrated is a gross exaggeration of the very slight relief which would exist as a result of a miniscule increment of subsidence over thickness of deposition in the basin. It is probable that if such a basin were available for study today, a casual observer could row a boat from the area of normal marine salinity into the area of high salinity and evaporite deposition without noting any change at the surface of the sea.

Excess evaporation under arid conditions removes water from the basin with replenishment derived from the open sea at the left. The intervening stable area, subsiding very slowly with reference to the adjoining basins, maintains a belt of shoal water which operates as an effective sill between the dense water of the saline basin and the normal marine sea water, while permitting the surface flow of sea water into the basin at the right. Bars, banks, and patch reefs may form and shift about in the shoaling belt without leaving identifiable deposits in the stratigraphic record.

The pattern continues as long as the basin subsides sufficiently to accommodate the accumulating evaporites. The greater the tectonic differentiation the greater the effectiveness of the sill and the more extreme is the evaporitic environment. Conversely, relaxation of subsidence in the basin or equalization of tectonism in the basin and sill areas permits the gradual restoration of normal circulation and a transition from saline, through penesaline, to normal marine environments spread over a uniform shelf.

As the diagram suggests, all the environmental phases from saline to normal marine, brackish and terrestrial may prevail side-by-side. Facies relationships of tectonically-silled basin evaporites confiem this. In the Mississippian of the Williston Basin area (fig. 4) for instance, normal marine limestones of the Rundle grade eastward from northwest Montana and south Alberta into evaporitic dolomites and anhydrites in central Montana and thence into the salt and anhydrite of the basinal Charles. At the eastern margin of the basin these beds appear to pass into red silts and shales of brackish origin.

Reef-enclosed Intra-basin Evaporites.—All intergradations between tectonically-silled basins and reef-enclosed basins may be expected. The latter classification is intended for those cases in which the major control may be shown to be related to reefing. This distinction is frequently difficult in the investigation of ancient stratigraphic patterns by means of subsurface data. Banks and bars of crinoidal, algal, and other bioclastic debris are natural attributes of the shoal waters on a restricting sill. These may appear in subsurface records as true reefs although they never had the topographic expression, wave-resistant structures, or reef-core and reef-flank relationships which are the hall marks of the biohermal reef.

Reef-enclosed evaporite occurrences are diagrammed in figure 7 and are typified by the later Silurian of the Michigan Basin area (fig. 2). The same tectonic and paleogeographic factors are invoked as in the previous case with the addition of sustained reef trends on the sill between the open sea and the basin, and, commonly, between the basin margins and the adjoining stable shelf areas. It would be theoretically possible for a reef ring to bring about the restriction of marine waters and the deposition of evaporites in the absence of tectonic factors, as within an atoll developed in an arid region. The maintenance of such conditions for a sufficient length of time to account for a significant thickness of evaporites can not be attained without a precise balance between rate of reef growth and rate of subsidence. The stratigraphic record suggests strongly that this equilibrium is established and maintained only along tectonic hinges such as serve to separate subsiding basins from their enveloping stable areas.

Basin-margin Evaporites

The second major category of evapo-

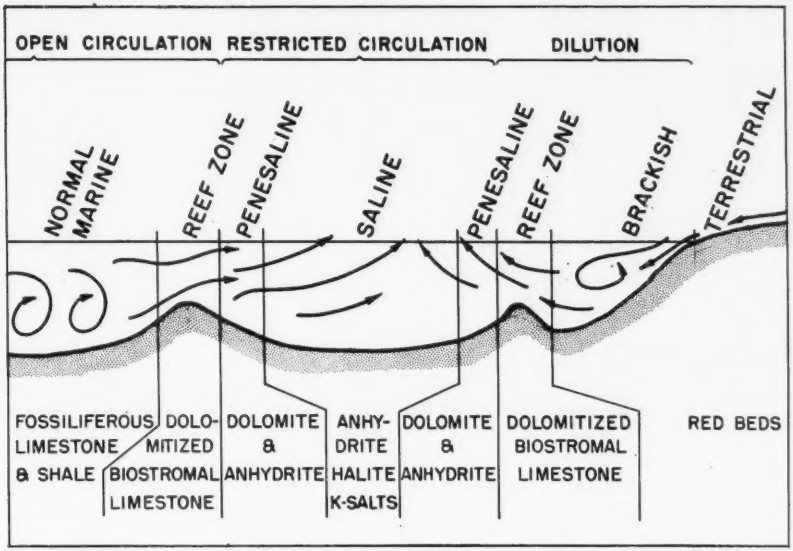

FIG. 7.—Diagrammatic profile showing relationships of topography and environment in reef-enclosed intra-basin evaporite accumulation.

rite occurrences involves those cases in which the central areas of the basins are the loci of normal-marine or euxinic environments while the margins of the basins and the neighboring shelf areas are the sites of evaporite accumulation adjoining a strand line in an arid climate. The peripheral evaporitic lagoons are separated from the intra-basinal waters by persistent reef barriers, by topographic features related to the tectonic hinge between basin and shelf, or by combinations of the two.

Difficulties of classification are again encountered in cases of basin-margin lagoonal situations of very great extent. Where very broad areas are involved these may exhibit minor tectonic features such as gently subsiding basins which add the restrictions of a tectonically silled basin to the regional restriction back of a reef trend. In the Late Senecan of the Alberta-Montana area, for instance, penesaline environments were widespread south of the Leduc-Redwater reef trend and north of the margin of the sea in central Montana. Within this broad back-reef tract minor isolated basins were the sites of tighter restriction and the development of significant thickness of anhydrite and salt. Similar patterns are observed in the early Permian salt basins of the Mid continent which are "basin-margin" types in terms of the barriers existing at the rims of the Midland and Delaware Basins.

Back-reef Evaporites.—Back-reef evaporite occurrences at the margin of a cratonic basin are exemplified by the Leonardian and Guadalupian evaporites of the West Texas-New Mexico area (fig. 1) and illustrated by Figure 8. Here the restricted ingress of marine waters through passes in the barrier reefs, coupled with the inhibition of return flow of dense saline waters from the lagoon, sets up the necessary pattern for evaporite deposition.

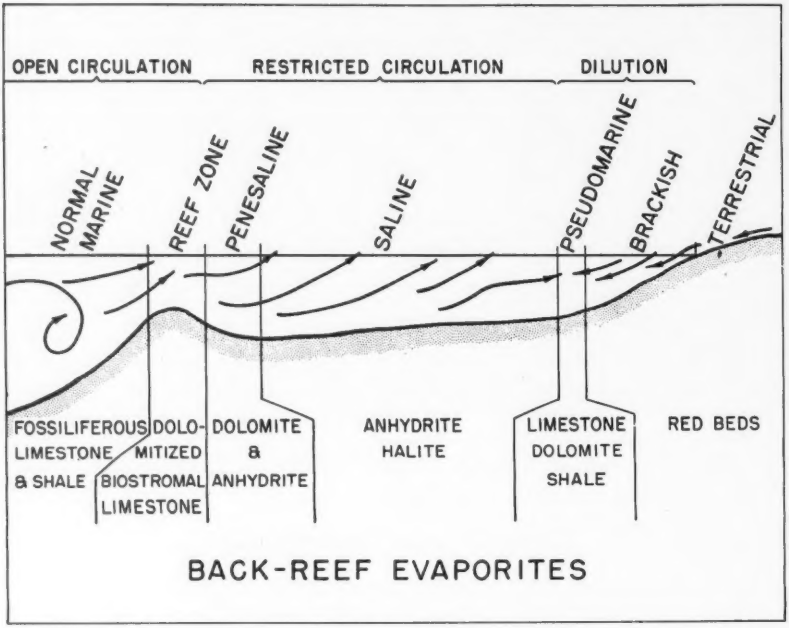

FIG. 8.—Diagrammatic profile showing relationships of topography and environment in back-reef basin-margin evaporite accumulation.

Topographically-silled Basin-margin evaporites.—This may be thought of as a "waste-basket" category into which are tossed those cases of basin-margin evaporites not demonstrably related to reefing. Certain of the isolated evaporites equivalent to the Gypsum Spring formation in the Jurassic of Montana and Saskatchewan, for instance, are marginal to the shallow Jurassic development of the Williston Basin. No reefs are evident and it must be assumed that the restrictions were imposed by minor bars or other geomorphic factors.

Such topographically-silled evaporites are transitional with thin and impersistent anhydrite and gypsum accumulations associated with red beds in broad and relatively stable shelf areas which have little in common with the basinal types under discussion.

SUMMARY

In summing up the writer's ideas, which are a synthesis of those expressed by many others, the following points emerge:

1. Major evaporite occurrences are indicative of a geographic position in a complex of depositional environments controlled by coincidence of climatic and topographic factors.

2. While the climatic controls remain obscure it may be shown that the maintenance of a submarine topography affecting evaporitic environments is strongly influenced by tectonism.

3. Cratonic tectonism is notably cyclical and is reflected in a predictable succession of depositional environments leading to the establishment of evaporitic conditions and back to the normal environments of the open sea.

4. The close relationship of major evaporites and contemporaneously subsiding basins makes possible a classification of evaporites, with further subdivisions based on the character of the restricting sill.

In closing, it should be made clear that the majority of data bearing on the problems of evaporites are derived from the subsurface. Evaporites are rarely well preserved in outcrop and where they are exposed the view is usually one-dimensional along the facies trend. Relationships between related facies are best studied in the solid-geometric framework provided by cores, samples, and mechanical logs. As these subsurface data expand with continued exploratory drilling some of the concepts expressed herein will require modification or replacement.

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FIGS. 1–5, SEPTEMBER 1953

ENVIRONMENT AND MODE OF ORIGIN AND FACIES RELATIONSHIPS OF CARBONATE CONCRETIONS IN SHALES[1]

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ABSTRACT

In Cretaceous shales and limy shales of the Magdalena Valley of Colombia, South America, occur many carbonate concretions. These concretions commonly contain such marine organisms as ammonites. Occasionally, one finds the full body of a fish, like the specimen in the accompanying photographs. The occurrence of carbonate concretions in central basin shale facies is common not only throughout the Cretaceous of the lengthy Andean geosyncline but in similar facies throughout the world. The occurrence of fish in a full or nearly full-bodied state of preservation in concretions is also quite widely known.

The manner of occurrence of most carbonate concretions in shales clearly indicates that their origin is syngenetic or early diagenetic. They were formed very soon after deposition, when the enveloping muds were still in a very plastic, unlithified state. For instance, the muds filled in alongside the concretions and, as a result of later compaction, they now "flow" around them. Also, the occurrence of fish and various other kinds of organisms in a full-bodied, uncompressed state indicates that their calcification and the enveloping concretion development were early enough to protect the carcass both from extreme decomposition and from the compressive effect of many thousands of pounds of subsequent overburden pressure.

The author points out that the central basin deposition environments in which most carbonate concretion-bearing shales were deposited was rather generally unfavorable, or of limited favorability, to carbonate deposition. Such environments are stagnant, hence usually charged with carbon-dioxide, and the degree of alkalinity (pH) is too low for calcium carbonate deposition. It is suggested, and some evidence is cited, that the rapid calcification of the organic core and the accumulation of the enveloping carbonate concretion in these generally unfavorable realms result from the creation of a favorable environment in the immediate vicinity of the organic material. An alkalinity adequate for rapid carbonate deposition from calcium-ion-rich waters may be locally created by the ammonia that evolves rapidly as soon as proteinaceous (nitrogen-bearing) organic matter begins to decompose.

Similarly, the limited decomposition, mainly anaerobic, of the organic matter that usually impregnates the deeper basinal muds may temporarily create an alkalinity adequate to cause calcium carbonate to be released from the lime-bearing solutions permeating the muds. This may explain the common calcareous character of shales in basins where pure limestones are largely restricted to the aerated shallow flank, shelf or lesser bottom-high areas.

INTRODUCTION

The problem of the nature and time of origin of concretions has long provoked speculation and controversy among geologists. The inspiration for writing these paragraphs is occasioned by the discovery of fossil fish in carbonate concretions in Cretaceous shales in the middle Magdalena valley of Colombia, South America. The accompanying photographs, figures 2 and 3, picture one of these specimens, together with a portion of the concretion and the mold in which the fish was embedded. Another photograph, figure 4, shows the nature of the concretion and its relationship to the shale in which it occurs.

The X on the accompanying sketch map, figure 1, indicates the approximate locality in Colombia at which the fossil fish were found. The concretion and fish specimen pictured here was collected in Quebrada Peralonzo in the Department of Magdalena about 17 kilometers S40° E

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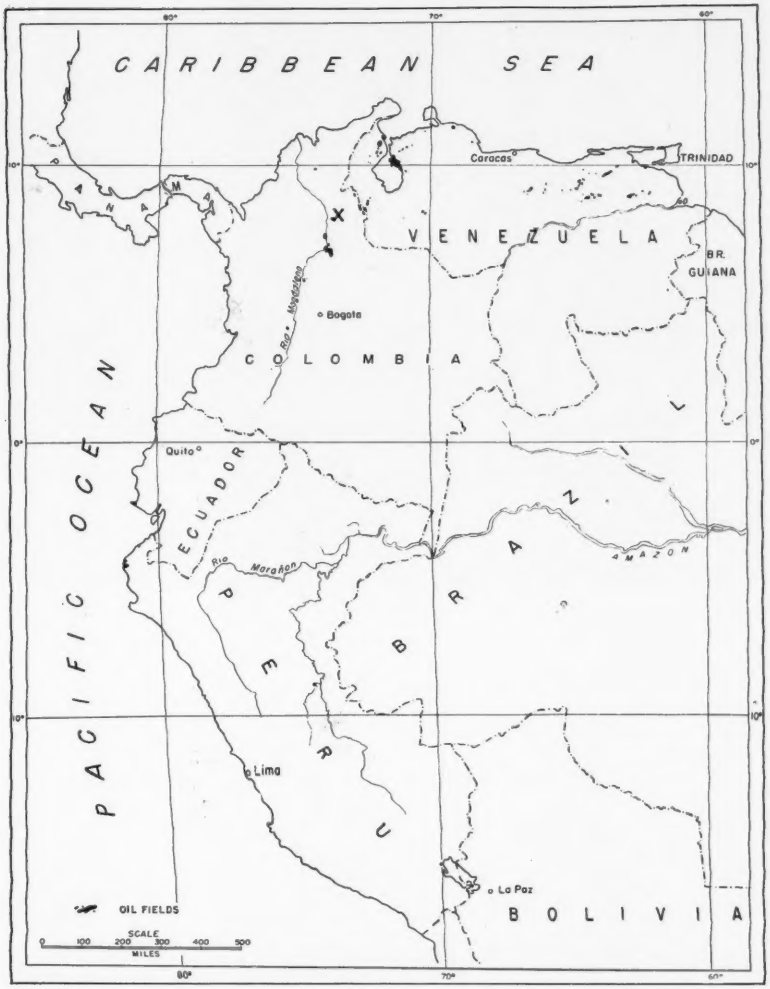

FIG. 1.—Locality (X) where fish-bearing concretions were collected.

from the town of Aguachica on the Gamarra-Ocana road.

ACKNOWLEDGEMENTS

Credit for the discovery of the fossil fish, as well as for the photographs of typical concretions and shales of the discovery locality, goes to Mr. Donald J. Podesta, geologist for International Petroleum (Colombia) Limited. To Mr.

FIG. 2.—Fossil fish embedded in calcareous concretion.

Podesta and to Mr. E. D. Ackerman, Exploration Department Manager for Intercol, acknowledgement is made for the description given below of the fossil fish occurrence. To both of these gentlemen and to International Petroleum (Colombia) Limited we are indebted for their interest in having this account published, and for their permission to have the specimen pictured here deposited with the collection of fossil fishes in the American Museum of Natural History, New York City. Thanks are also due the Public Relations Department of the Standard Oil Company (N.J.) for making and supplying the photographs of the fish for this paper. We are particularly thankful also to have been able to enlist the aid of Dr. Bobb Schaeffer, widely experienced student of fossil fishes and Associate Curator of Fossil Fishes at the American Museum of Natural History in New York City, for a study of the fish specimen.

BASIN SETTING AND LITHOLOGIC RELATIONSHIPS

The shales in which the lime concretions occur are a part of a thick Cretaceous marine series which also contains limestones and well-defined zones of dark bituminous cherts. Sands are present, too, but in relatively limited development. These occur mainly along parts of the basin flanks, particularly at or near the base of the Cretaceous transgression and again in the regressive phases that close the Cretaceous cycle.

This great series of sediments was accumulated in a geosyncline which extended along the present Andean belt from the island of Trinidad westward through Venezuela, and then southwestward and southward through Colombia, Ecuador and Peru. The thickest part of the Cretaceous accumulations of the geo-

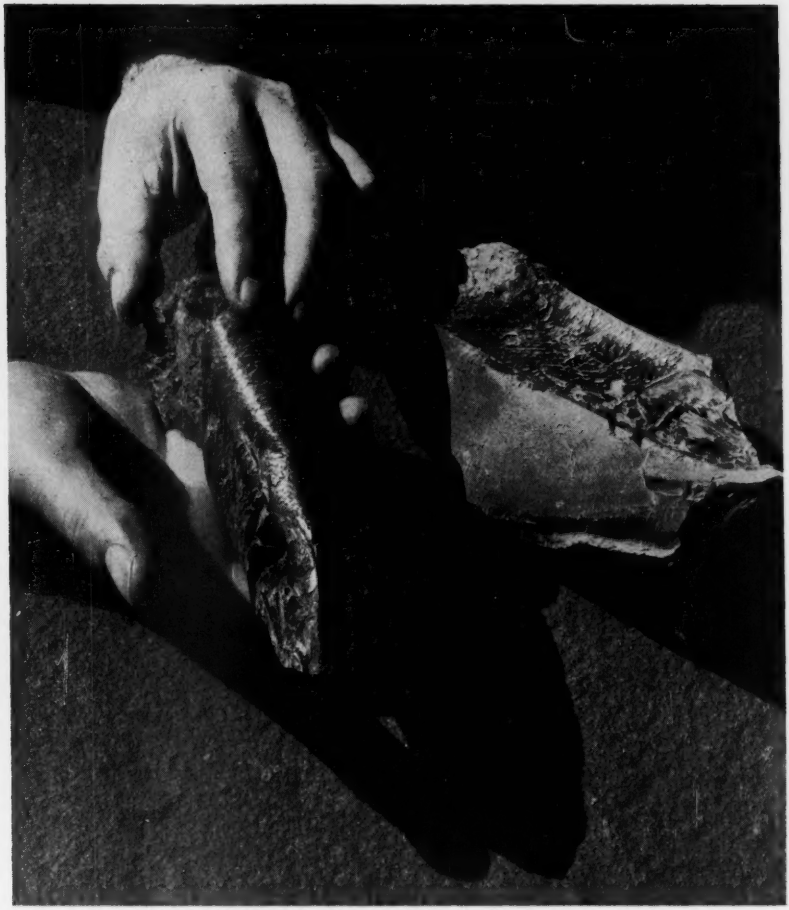

FIG. 3.—Fossil fish removed from concretion. Note absence of flattening of the fish body: this suggests lithification before compaction of the enclosing shales occurred.

syncline are now largely incorporated into the mountain rocks of the Tertiary-Quaternary Andean chain.

The shales of the fossil locality are of middle Cretaceous age. They appear to be approximately lower Albian. Similar shales may be seen at many places along the Andean geosyncline. They are dark, bituminous and calcareous. Shaly limestones are also present in the sections. As is usual, essentially pure limestones are confined to times as well as areas of little terrigenous sediment influx. They are also largely restricted to the aerated bottom areas such as the broad shallow basin shelves, but they may accumulate

FIG. 4.—Calcareous concretion embedded in dark-colored shale. Note curvature of shale bedding around the concretion.

more widely over the basin during periods of less extensive stagnation.

DESCRIPTION OF CONCRETION OCCURRENCE

The shales immediately associated with the fish-bearing concretions are thinly plated, black and calcareous. Concretions are abundant through this part of the section. They are generally spherical to oval or oblong and slightly flattened parallel to the bedding. The concretions range in size from a few centimeters to approximately eight meters along the longest diameters.

The concretions are usually composed of carbonate, largely calcium carbonate. However, they are occasionally argillaceous, or siliceous. They range in color from gray to black, are usually dense and hard, and they have a distinct petroliferous odor when freshly broken. More often than not, they contain ammonites rather than other fossils. Not uncommonly, oil droplets, oil blebs, or oil staining are found inside the ammonites of the concretions. The color of this oil ranges from green to black and tarry.

The association of carbonate concretions with a stagnant water shale, marl or argillaceous limestone facies is very common over the world. Likewise, the relationship of the bedding to the concretions in this type of occurrence is also rather general. Figure 4 clearly shows that the bedding in the shale bends or "flows" around the concretion both above and below. This is typical of the relationships throughout this area. It indicates that such concretions developed very early after deposition. But we shall come back to this and other interesting speculations after a brief description and discussion of the fossil fish.

DESCRIPTION OF THE FOSSIL FISH

Following his study of the fossil fish, Dr. Bobb Schaeffer of the American

Museum reported as follows:

"The specimen belongs to a family of teleost fishes called the Elopidae which includes the living ten pounders, and, in some classifications, the tarpon. This taxonomic allocation is indicated by the size and shape of the preserved bones in the circumorbital series, as well as by the nature of the opercular series. Unfortunately, the specimen is not complete enough to make a positive generic identification. In order to determine the genus, it would be necessary to have a reasonably complete skull roof as well as the posterior portion of the body showing the structure and position of the pelvic, dorsal, anal and caudal fins. There is a good possibility that the specimen represents a new genus. Although it resembles the Brazilian *Rhacolepis* in scale ornamentation and in certain other features, the differences are great enough, on the basis of the available evidence, to consider it distinct. The same is true when comparisons are made with the other genera described by Jordan from the Cretaceous of Brazil.

"The elopids from the late Cretaceous on the northeast coast of Brazil were considered by Agassiz in 1841. Perhaps the most important contributions are those of Jordan (1921), Woodward (1901), and Dunkle (1940). The richest locality for these forms is at Barra do Jardim, State of Ceara in the Formacao Santana of the Serie Araripe. Here the fishes occur, often 'in the round,'[3] in limestone concretions.

"Perhaps it is reasonable to assume that other concretions at the Colombia locality contain fishes. Should this be the case, the additional specimens would undoubtedly yield the required information on skull and body morphology. Although the resemblance of this form to the Brazilian elopids suggests that it is Cretaceous in age, it is important to note that this family of fishes has had a conservative evolution and that it occurs widely in marine deposits from the early Cretaceous to the Quaternary.

"There are numerous other localities, of various ages, that have fishes in concretions. For instance, the Upper Devonian Cleveland shale of Ohio has large limestone concretions that frequently contain arthrodire fishes. These are usually partially or completely flattened. This same formation also has fish bones embedded directly in the shale. Molds of uncrushed or partially compressed fishes have been found in the Middle Pennsylvanian beds at Mazon Creek, Illinois, in the Texas Permian and in the Lower Triassic of Madagascar. The Upper Jurassic of Western Cuba contains beautifully preserved fishes in black limestone concretions and these require acid preparation or sectioning for study. The most recent examples of concretionary formation around fish remains are probably found in Greenland and northern Canada. These concretions are generally considered to be post-Pleistocene in age and are frequently shaped like the fish *Mallotus* contained therein." (See fig. 5.)

COMPARISON WITH OTHER FISH-BEARING CONCRETION OCCURRENCES

The degree of "compression" undergone by the fish in the various fish-bearing concretion occurrences represented by the numerous specimens at the American Museum varies from negligible to appreciable. As a general rule, they are not extensively "flattened."[4] In the Madagascar lower Triassic the fish are encased in marine limy sand concretions. In most of these specimens the body of the fish is largely disintegrated. The disintegration apparently took place after the formation of the concretion, leaving a hollow mold which has the original form of the fish. An impression of the fish can be seen on the limonitic face of the mold.

[3] A phrase used to indicate that the specimen is full-bodied; that is, undiminished or very little diminished in form and dimensions from its original condition in life.

[4] See footnote 6.

In the case of the Upper Devonian Cleveland shales, the fish are in black carbonate concretions, but bones of the fish also occur separately in the shales. The fish-bearing black carbonate concretions of the Upper Jurassic of Cuba are in bituminous shales and shaly limestones. The environment of deposition was apparently similar to that of the Colombia concretion-bearing sediments.

Hundreds of examples of carbonate concretion-bearing shales, limy shales or shaly limestones might be cited over the world. Generally speaking, the environments of deposition were similar in all of them. A typical example is the concretion-bearing shale and shaly limestone facies of the relatively deeper stagnant basin belt or areas of the Cretaceous geosyncline of Mexico. Among the numerous examples that are perhaps more familiar to us are the concretions in the Mowry, Carlisle and other Cretaceous shales of the Rocky Mountain and adjacent states.

TIME OF CONCRETION DEVELOPMENT

Views on the time of origin of concretions in general may be grouped under two headings:

1. Syngenetic. Formation at the time of deposition of the containing sediments (or very shortly thereafter—diagenetic).

2. Epigenetic. Formation subsequent to the lithification of the containing strata.

Perhaps representatives of both of these times of origin exist among concretions.

While references to concretions are quite common in the literature, there are comparatively few data convincingly fixing both the time and the manner of origin. It appears to the writer that in the past an epigenetic origin has been favored by the majority of those who have expressed an opinion in the text books and other literature. An epigenetic origin may explain the formation of certain kinds and compositions of concretions in permeable strata. In some of these occurrences the bedding continues on through the concretion. They are clearly not strictly syngenetic.

In the case of the very widespread and abundant occurrence of carbonate concretions in shales, calcareous shales and argillaceous limestones, there seems to be little doubt of a syngenetic or early diagenetic origin. W. A. Tarr (1921) appears to have been one of the first, as well as one of the few, to have called attention to the convincing array of evidence for a syngenetic origin of this most abundant kind of concretion. Tarr lists nine lines of widely verifiable evidence. He shows that the physical relationship of the containing shales to the concretions is clearly one of envelopment during deposition or while the sediments were still in a very plastic state. He points out that it would be impossible after lithification of the shales to aggregate the calcareous material into a concretion, or to obtain the very distinctive physical relationships that exist between the shales and the concretions.

The clear evidence of a syngenetic origin for carbonate concretions in shales makes one wonder how common such an origin may have been for concretions in noncompactible sediments where such an origin is difficult to demonstrate on purely physical evidence.

Among the most interesting occurrences of fish-bearing concretions are those that are being found in Recent or sub-Recent marine clays in various places along the coasts of Greenland and northern Canada. Figure 5 shows one of these specimens from the American Museum which Dr. Schaeffer kindly permitted the writer to have photographed. The concretions occur in marine clays which apparently were raised above sea level by the isostatic rebound that followed the melting of the Pleistocene ice cap. The fact that concretions have already been developed in these very young clays seems significant.

In the writer's opinion, concretion development is, in most cases, just one of many diagenetic processes that occur in sediments during the period of physical,

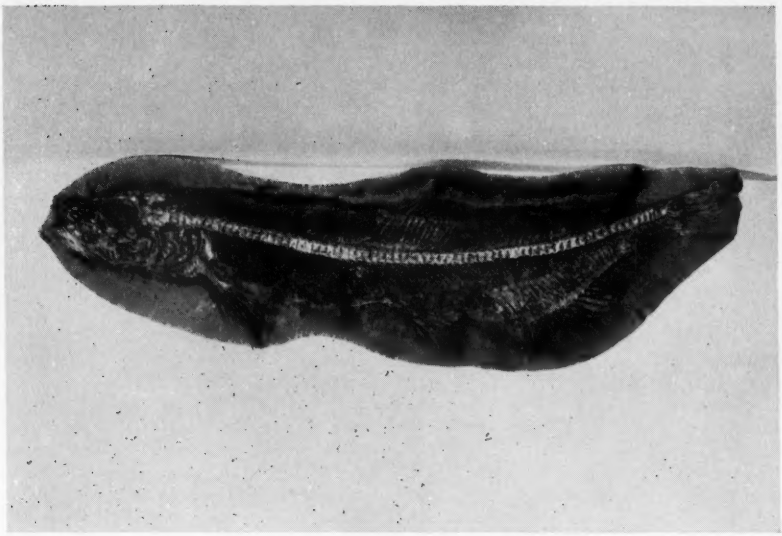

FIG. 5.—Post-Pleistocene *Mallotus* fish-bearing concretion.

chemical, biochemical, and mineralogic instability occasioned by the radically new environment in which sediments find themselves upon deposition. As stability becomes established in balance with this new and different environment the changes correspondingly cease.[5]

There are many direct and indirect lines of evidence which indicate an early evolution of most of the post depositional phenomena that we find in sediments. We shall dwell only on the fish-bearing concretions and some of the more obvious relationships.

The fact that the fossil fish which occur in concretions are so generally full-bodied or "in the round" indicates that calcification and concretion growth was early enough to protect the fish from the compressive effects of overburden, amounting in many cases to thousands of pounds per square inch. For instance, the sediments in which the Colombia specimen was contained were once buried beneath 10 to 15 thousand feet of younger Cretaceous and Tertiary rocks, and hence were subjected to pressures of at

[5] The evolution of petroleum is apparently another result of the early changes that occur in sediments, organic as well as inorganic. Conviction on this point resulted from an intensive world-wide study of oil occurrence made by the writer extending over many years. Other studies carried on in the past few years confirm that petroleum hydrocarbons occur widely in Recent sediments. See "Preliminary Note on Origin of Petroleum" by Paul V. Smith, Jr., in the February 1952 Bulletin of the A.A.P.G., pages 411–413. By his studies, Dr. Smith demonstrated for the first time that liquid paraffine-naphthene and aromatic hydrocarbons, similar to those found in crude oil, exist in recent marine sediments and may be extracted from them. Since publishing his note, Dr. Smith has examined recent sediments from numerous additional localities with the same result. See also "The Occurrence of Hydrocarbons in Recent Sediments from the Gulf of Mexico" by Paul V. Smith, Jr., *Science*, October 24, 1952, pages 437–439. In this more recent article Dr. Smith explains in more detail the methods and results of his investigations.

least 10,000 pounds per square inch.[6] The manner in which the shale strata bend or "flow" around the concretions also indicates early concretion development, and subsequent compaction of the soft fluid-bearing muds around them.

Several observers have, in the past, pointed out the excellent, in many cases perfect, state of preservation of fossils, both plant and animal, contained in the concretions found in shales. This fact they logically consider to be indicative of a syngenetic origin. Leo Lesquereaux (1870) describes concretions in Pennsylvanian shales in Grundy County, Illinois, where carbonate of iron concentrically developed around nuclei such as plants, bones of fishes, the remains of insects, crustacea, etc. The size and form of the concretions vary with those of the body around which the deposit was made.

It is of interest to note in passing that this last statement applies perfectly to the Recent fish-bearing concretions in the clays along the coasts of Canada and Greenland already described. Many of these specimens look as if the remains of the fish had been rolled in a batter, which subsequently lithified and so retained the form and dimensions of the fish.

Lesquereaux emphasized the perfect preservation of even the finest and most delicate parts and structures of the plant or animal, "just as if they were in life, or as if they had been transformed into stone while still living." He remarks on the absence of any flattening. He considers that formation of the concretion must have occurred very early to have accomplished such a perfect preservation. David White came to the same conclusion from his observations of similar fossil-bearing concretions.

VIEWS ON THE ORIGIN OF CARBONATE CONCRETIONS IN SHALES

The writer has seen little of a convincing nature in the literature concerning the manner of formation of carbonate concretions in shales. For that matter, the manner of origin of all types of concretions still appears very controversial.

Why do calcareous concretions develop around a piece of organic matter, such as a fish, an ammonite, or around any kind or organic material? The question is particularly pertinent since wide-scale carbonate concretion development occurs mainly in just those facies in which limestones are not present, or in which they occur in very impure form.

In other words, concretions of the kind described here are characteristic of those parts of the basin where a stagnant water environment prevailed. Any oxygen is quickly used up. Stagnation tends to inhibit the removal of the carbon dioxide that accumulates in such an environment. Hence the lime is largely retained in solution as the bicarbonate. Such environments today are usually of a low oxidation-reduction potential (E_h). They contrast importantly with the carbon dioxide-free environments of relatively shallow, aerated bottoms, such as those of the basin shelves and less extensive bottom highs.[7]

There seems to be no direct relationship between calcium carbonate deposition and the oxidation-reduction potential. The potential of a stagnant environment ordinarily ranges from low positive (only slightly oxidizing) to negative or reducing, but it is the stagnancy rather than the low O/R potential that facilitates retention of lime in solution.

Actually, the deposition or non-deposition of calcium carbonate is controlled mainly by the hydrogen-ion concentration (pH). Any one or any combination of a number of causes for the removal of carbon dioxide (such as increase of temperature, agitation and aeration, decrease of CO_2 pressure in the

[6] Examination of the fossil fish from various parts of the world seen by the writer suggests to him that in those specimens which show reduction in size or "flattening" this resulted from partial decomposition prior to calcification rather than compression.

[7] It is in the latter type of environment that excess calcium carbonate is most readily removed from the waters; and if there is negligible influx of sands or other terrigenous clastics these are the areas where the purest limestones are usually accumulated.

atmosphere, etc.) tends to increase the pH and hence favors the deposition of lime. Conversely, anything which lowers the alkalinity of the waters or even throws the environment into the acid range changes the balance in favor of holding the lime in solution. Sea waters are normally alkaline, with a pH ranging from about 7.5 to 8.5. A neutral solution has a pH of 7.0 and decreasingly lower values represent increasing acidity. Normally, calcium carbonate deposition requires a pH at least as high as 7.5.[8]

Why is it that in an environment generally unfavorable for pure limestone deposition, such as that of the Cretaceous shales of Colombia and many other similar shales, calcium carbonate concretions can develop locally around, say, an ammonite or a fish? Something must happen here which sets up a very localized environment favorable for the accumulation of calcium carbonate.

[8] The removal of silica from the lands and the deposition of chert from silica-bearing waters after entering the sea is another phenomenon that is in large part dependent on the pH of the environment. Sea waters carry only very slight amounts of silica. The large quantities carried to the seas are quickly precipitated. Adjacent vulcanism, both submarine and subaerial, have been evident sources of silica at various times and places over the world. However, periods of extensive peneplanation are times when dissolved silica comprises a rather appreciable percentage of the diminished quantities of materials transported to the sea from the land. The conditions favor concentrated silica precipitation as well as of lime and mud deposition. This fact and the physical chemistry involved partially explains their common association. Chert and the lime and mud facies with which they are associated occur in characteristic positions with respect to the basin bottom form and environment that control their place of deposition. For that matter, environment controls the precise place of deposition of any mineral, whether that deposition be in sediments or in igneous or metamorphic rocks, and whatever the genesis may be. Again, we see the fundamental importance of environment in the treating of ores, like those of carnotite, for instance, where the control of pH to a rather delicate balance is very essential. The occurrence of all phenomena depends upon some distinctive environment, commonly a very precise one.

The preservation of organic matter in the bituminous shales indicates a reducing environment, or the very early development of such an environment upon burial. The presence of organic matter in itself would tend to decrease the E_h. But the oxidation-reduction potential has little or no direct influence on carbonate deposition. Whatever the influencing agent is, it must be one which renders the immediate vicinity adequately alkaline.

There are probably few stagnant bottom environments where there is not some limited decomposition of organic matter, even if anaerobic. Bacteriologists and biochemists tell us that where there is anaerobic decomposition there is a localized concentration of ammonia or amines. This would markedly increase the pH; it would be sufficient, no doubt, to precipitate the bicarbonate in solution as carbonate. One of the tests used by bacteriologists to determine if the bacterial process is progressing is to see if ammonia is evolving.

Once the initial concentration and precipitation of calcite crystals ("seeding") started, the process would probably continue for some time. Perhaps, in the case of many concretions, seeding might be effected by some form of carbonate, such as a fragment of aragonite from a shell, with resultant concretion development.

The writer had occasion to discuss his thoughts as expressed in this and final sections of this paper with Professor Walter H. Bucher of Columbia University. We are indebted to Professor Bucher for calling attention to certain experimental observations recorded by Dr. Franz Hecht (1933) on what happens to the carcasses of animal organisms or portions thereof on the sea bottom or on burial at shallow depths in the sediments. The experiments were made along and just off the beach of the 30-mile-long Jade Bay leading to the port of Wilhelmshaven on the north German coast.

Among the various forms of animal matter studied by Dr. Hecht was the body of a shark which surveyors had found stranded in 1924 near the outer

edge of the largest tidal flat. They buried the body of the shark beneath a meter of sand at the locality where it was found. They then marked the spot and left the carcass there for two years. The shark was uncovered in 1926, when it was found that it had not changed noticeably in form. The specimen was again examined in 1931. Parallel studies of dead animal organisms were made in aquaria in the laboratory to check those on the near shore sea bottom. Though we have no quantitative data on the oxidation-reduction potential or the pH of the respective environments, and the contents and degree of saturation of the sea water, etc., some of the findings are of interest to us.

It was found that the albuminous or proteinaceous (nitrogen-bearing) substances decomposed very much faster than did the fatty constituents. The nitrogen is released in the form of ammonia or amines, which is as we had previously observed. Thus a degree of local alkalinity might be reached favorable to the deposition of calcium carbonate, if the conditions of saturation, etc., were adequate in that area. Nitrogen escapes much more rapidly as ammonia, etc., than does the carbon as CO_2. This accounts, as Hecht notes, for the greater ratio of carbon to nitrogen in the organic matter of sediments than that known in living bodies, as was observed in many cases by Parker Trask.

Incidentally, several other observations recorded by Hecht are of interest. He reports that the end-product of retarded decomposition is a homogeneous solid substance. It seems there was some difference of opinion whether this substance was adipocere. Adipocere is a waxy brownish substance generated in dead bodies that have been long buried or immersed in moisture. Particularly, it is said to accumulate from bodies that have lain for some time in sea water. Hecht also observed that the more resistant fatty substances of the animal body may penetrate the enveloping sediment and cement it, concretion-like. This condition was observed, for instance, in the case of the shark.

One other finding of Hecht is of interest in connection with our earlier statements about the role of carbon dioxide in dissolving calcium carbonate and retaining it in solution. It was observed that the carbon dioxide evolved during organic decomposition had a marked solvent effect on shells and bones. Probably most limestone is of organic or biochemical origin. On its decomposition, which is the inevitable fate of most organic life, the organism reverts to the stable products, carbon dioxide and water, from which it originally derived. The writer believes that it is this carbon dioxide, which is released to the solutions permeating newly deposited carbonate sediments, that is responsible for many distinctive features of certain well-defined basin facies of carbonate rocks. The features referred to include the vug to pin point porosity, the remarkable permeability, the solution and recrystallization, the early forms of calcite veining and other features that are peculiarly characteristic world wide of carbonate rocks formed in certain belts or areas of basins. Without doubt, they correspond to well-defined environmental ranges of pH and E_h, degrees of circulation or stagnancy, origin and rate of deposition, etc. (Weeks, 1952).

ORIGIN OF LIME IMPREGNATION OF MUDS

The Cretaceous basins of the Andean geosyncline are typical of many in which limestones and shales predominate. Environment determines the facies left at any position on the deposition bottom of any basin, and shales are a characteristic facies of the relatively deeper stagnant environment. Depending on the concentration balance of the respective ions, these shales may be slightly to very limy and the facies may range to impure limestones. Organic matter, which is completely decomposed in an aerobic environment, normally is not oxidized or may be only partially decomposed in the quiet stagnant environs

of a basin. The resulting sediments usually are or once were bituminous.[9]

If there is any merit to the suggestion that many concretions owe their formation in a generally unfavorable realm to a localized environment made adequately alkaline around a piece of organic matter, perhaps to some degree the lime impregnation of shales deposited in lime-bearing waters in a stagnant environment may be similarly explained. The limited decomposition, mainly anaerobic, of the organic matter that normally impregnates such muds may create, at least temporarily, a pH sufficiently high to permit calcium carbonate to be released from the lime-bearing solutions permeating the muds. The degree of resultant liminess would probably depend, too, on the ion concentration and balance, and also on the relative amount of the noncarbonate mud supply.

The excuse for this paper is a mere concretion, albeit a rather special and intriguing one. We cannot presume to have indicated complete solutions for the problems posed. But perhaps we have suggested some new paths of thought. It is hoped at least that we have helped to stress how an understanding of a simple phenomenon such as may be passed unheeded day after day in the field may give us an insight into many of our major problems. If we have done no more than this, this paper seems worth while.

[9] The extent to which these sediments remain bituminous may depend upon the degree to which the clay or lime muds have given up their bitumen as hydrocarbons. It may also depend on how much of these fluid hydrocarbons, once formed, have been able to migrate to more porous facies.

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FIGS. 1–4, SEPTEMBER, 1953

SILICIFICATION IN THE ONEOTA DOLOMITE

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ABSTRACT

A short description of silicification in the Oneota dolomitic member of the Lower Ordovician Prairie du Chien group in the form of silicified stromatolite colonies and chert nodules near El Paso, Wisconsin is given. The occurrence of chert pebbles showing dehydration cracks and other evidence indicate that silicification took place during the time of the sedimentation.

The following paper is a result of the writer's field observations in June 1952 which give some new evidence concerning silicification in the Oneota dolomitic member of the Lower Ordovician Prairie du Chien group.[1] The area studied is located just south of El Paso, Pierce County, Wisconsin, in secs. 5 and 8, T. 26 N., R. 16 W. on both banks of the steep Rush River valley, cut mostly in the Oneota dolomite.[2] Several outcrops show massive, granular, oolitic, microbrecciated, porous and cavernous dolomites. At many places the rock is cherty, as in other localities in the Middle Western states (Bain and Ulrich 1905, Chamberlin 1878–83, Powell 1935, Schwartz 1936, Stauffer and Thiel 1941, Thwaites 1923, Ulrich 1924, etc.). Fossils other than common stromatolite (cryptozoon, e.g. Cloud 1942) colonies are very rare, but the writer found a piece of chert about 20×30 cm in size that contained 20 fossils (fig. 1A). *Ophileta* sp., *Sinuopea* sp., and *Clarkeoceras* sp. were identified by Dr. W. C. Bell. The preservation of fossils in chert in the Oneota is also typical in many other localities (Powell 1935, Schwartz 1936, Stauffer and Thiel 1941, Twenhofel and Thwaites 1919, Ulrich 1924, etc.).

[1] The writer is much indebted to Dr. G. A. Thiel and to Dr. W. C. Bell for a discussion of the problem and for reading the manuscript.

[2] According to the geologic map of Pierce County (Hotchkiss and Steidtmann, 1914, plate 38) the valley floor south of El Paso is cut in the Cambrian sandstone.

The most typical outcrop in the area studied is located in the NE¼ sec. 8 on the east bank of the Rush River, three-fourths of a mile SSE of El Paso, just north of the small tributary valley in the middle part of the slope. Here about 38 feet of dolomite is exposed. Silicification, almost absent in the lowermost 6–8 feet of this outcrop, is common in the upper 15–18 feet where it is represented by 3 types of silica aggregations. They occur as follows:

I. Rounded smooth nodules of gray chert 2–5 cm long, and horizontal layers 1–10 cm thick. The nodules usually lie horizontally, parallel to the bedding; less commonly, in stromatolite colonies, they are inclined to the major bedding and are parallel to the stromatolite laminations (fig. 2). In some places the chert shows an oolitic structure and in thin section is composed of numerous oolites with well-developed concentric structure. Most of the oolites are circular in outline but some are oval-shaped and consist of several smaller concentric structures. The oolites are composed of fine chalcedonic material, more rarely, of a mosaic of quartz aggregates. In some oolites spots and rings of fine crystalline carbonate are seen. The oolite-bearing matrix is represented by microcrystalline silica and carbonate, more or less isolated or intermixed. This type of silicification is not common.

II. Horizontal silicified zones 10–300 cm long and 1–5 cm thick with botryoidal upper surfaces coated by small quartz

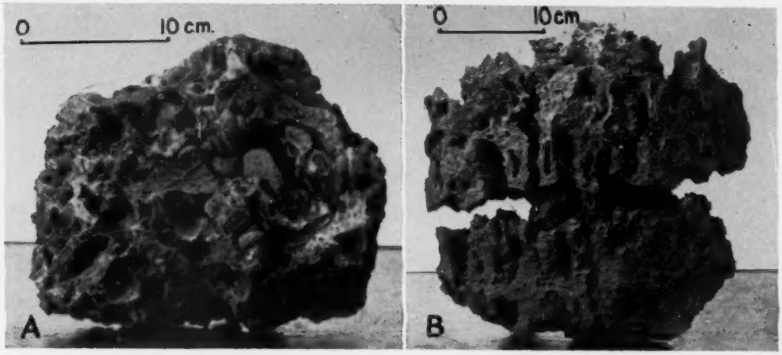

FIG. 1.—*Silicification in the Oneota dolomite. A, preservation of the Oneota fauna in chert.* Right bank of the Rush Valley one-half mile south of El Paso, Wisconsin. B, silicified columnar cryptozoons in two layers in the Oneota dolomite. Dolomite between cryptozoons has been *strongly leached by weathering. Left slope of Rush River at Johnes' Farm.* SE¼ sec. 5, T. 26 N., R. 16 W., Wisconsin.

crystals. The lower boundaries may be *gradational or show irregular features* such as worm (?) trials, which may occur also on the upper surface. Morphologically this type is similar to "*Cryptozoon minnesotensis*" (Winchell 1896, Chaney 1891) which also shows penetrations by various boring forms (Stauffer *1945, p. 378). Similar forms are known* also as "cabbage" and "cauliflower" structures (Powell 1935). *Thin sections* through such silica crusts show a zone of a fine mosaic of microcrystalline quartz underlain by irregularly grained carbonate. A short distance from the carbonate *base the quartz grains become larger and* go over into well-developed quartz crystals of different sizes and orientation. The crystal forms are conspicuous because of several parallel lines of fine inclusions which continue through neighboring crystals and thus show former crystal faces.

III. Silica aggregations similar in form to a column stromatolite occur as vertical, irregular, branching "pipes" of gray flint 20–35 cm high and 2–5 cm in diameter with hollow interiors covered with quartz crystals. In cross sections pipe-bearing rock has a honeycomb pattern. The upper ends of the columns are more or less free; *the lower ends are mostly* connected in a basal plate 5–25 cm thick *penetrated by irregular cavities. The* floors of the colonies are flat or wavey. Thin sections reveal a mosaic of fine quartz grains with many spots of chalce-

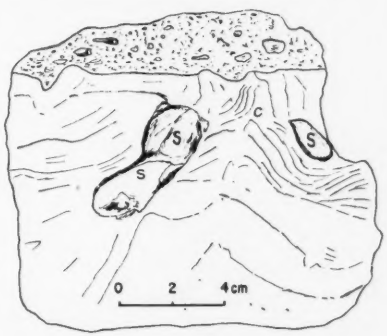

FIG. 2.—Sketch showing the relationship between two chert nodules (S) and cryptozoon colony (C) in the Oneota dolomite. The cryptozoon is similar to the form described by Chaney (1891). The overlying dolomite is porous and microbrecciated. From the middle part of right slope of Rush River at old water mill, south of El Paso, Wisconsin.

donic silica. In a few places small inclusions of carbonate were observed. The cavities are covered by quartz crystals similar to those referred to above. In several outcrops such structures occur in 2 or 3 zones at vertical intervals of 6–15 cm (fig. 1B).

The quartz crystals are characteristic of the second and third types of silicification, and seem to be common also in other areas where they are known as "geodes," cavities etc. (Bain and Ulrich 1905, Chamberlin 1878–83, Powell 1935, Stauffer and Thiel 1941, Twenhofel and Thwaites 1919). The crystals are .5–1.5 mm long and have white, rose, amethystine, reddish and brownish colors. The color may be variable even in a hand specimen, but the reddish-amethystine color is especially common. Red crystals usually are underlain by darker red quartz and this in turn is underlain by black zones of microcrystalline quartz .5–3 mm thick. In one specimen pyrite was found in this lining zone under dark brown quartz.

The uppermost 15 feet of the outcrop is very low in silica. Stromatolite colonies in the form of rounded, 40–60 cm thick "caps," 70–100 cm in diameter were seen on the top of the bluff. The caps are built of concentric crusts of honeycomb structure somewhat similar to *C. rosemontensis* (Stauffer 1945) and *C. ozarkensis* (Powell 1935). Some oolitic grains were observed. In thin section the stromatolites are made up of fine carbonate minerals without any evidence of cellular structure.

Both above and below the colonies of stromatolites the rock contains many dolomitic pebbles which, in the main, are flat and rounded with smooth surfaces (fig. 3A). They range in length from .5 to 5 cm. Some bedding surfaces show mudcracks which may have contributed fragments that formed some of the flat pebbles (fig. 3B). Many of the pebbles are oriented parallel to the bedding but others are arranged irregularly. The matrix of the conglomerate is finely brecciated and often sandy. The pebble-bearing zone is widespread and at some places it contains chert pebbles along with the flat dolomite pebbles. The chert pebbles are oval in outline and .5–7 cm long. Many appear to be brecciated. The pebbles surfaces are always covered by mudcracks produced by dehydration of a silica gel (fig. 4A-D). Some pebbles show a chert nucleus with a coating of dolomitic mud 1–5 mm thick to form mud balls (fig. 4E, F). Both nucleus and coating show dehydration cracks and the nuclei at some mudballs are broken. In thin section the nucleus of the fine chalcedonic mineral is covered with a carbonate crust composed of very fine grains. Along the contact between silica and carbonate there appears to be an invasion of carbonate dust into the chalcedonic material which seems similar to diffusion banding or rings. The large crack in the nucleus is filled with coarser grained silica and carbonate. One dolomitic pebble has an unusual chert coating (fig. 4G). Its nucleus does not show signs of shrinking but the coating has several fine dehydration cracks.

The nature of the conglomerate is not clear. Similar rocks may be developed by water movement in shallow sea, especially near bioherms (Lochman 1949, pp. 51–58). However, the dehydration cracks in colloidal silica gel suggest a short period of drying of a small area (near an island?), perhaps between tides. There is no evidence for long intervals of drying over a large area. Chert pebbles are known also in other positions in the Prairie du Chien group (Bain and Ulrich 1905, Dake 1921, Ulrich 1924).

Higher on the slope there are several outcrops of dolomite, sandy in some places, but without important aggregations of metacolloidal silica. Near the top of the slope several pieces of white and brown sandstone were found, representing the New Richmond (Root Valley) member of the Prairie du Chien group.

The origin of the Oneota chert is not clear (Powell 1935, pp. 27–29). Twenhofel (1932, p. 715) states that this is a syn-

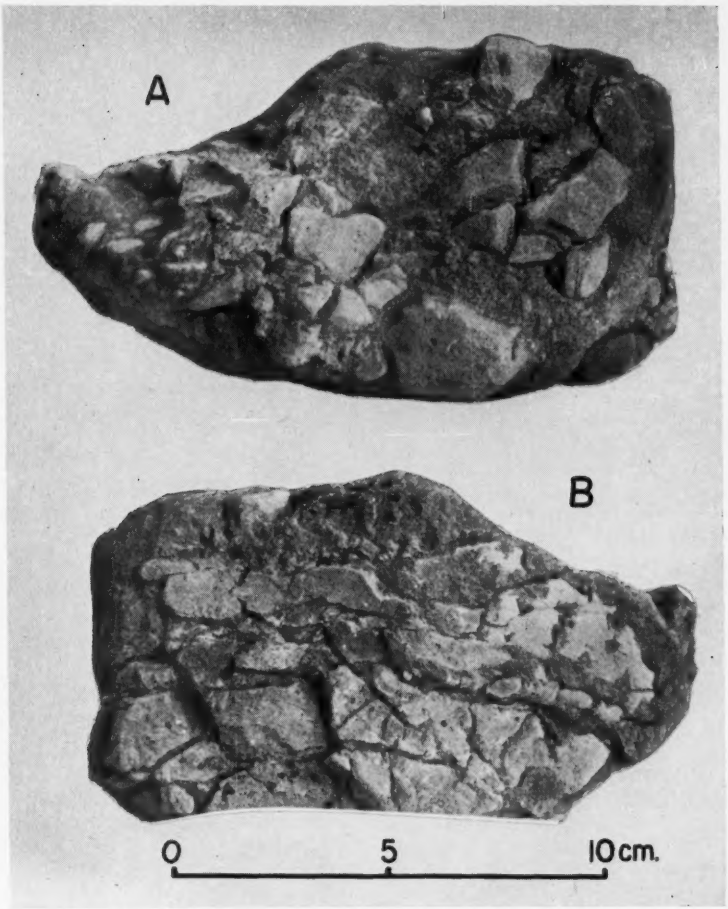

FIG. 3.—A, Specimen of flat-pebble conglomerate above the top of large outcrop in NE¼ of sec. 8, T. 26 N., R. 16 W., Wisconsin. B, Bottom surface of the same specimen showing smoothed mudcracks. Similar cracks may have been the source of pebbles.

genetic deposit, but according to Ulrich (Bain and Ulrich 1905, pp. 27, 28) and Bridge (1930, pp. 86–89) similar chert in the Lower Ordovician of Missouri is a result of selective epigenetic silicification on slopes.

However, the occurrence of chert pebbles with dehydration cracks in beds near the top of the Oneota dolomite cannot be explained by epigenetic silicification, and it suggests the deposition of silica gel in mud which was partly reworked in a shallow basin of sedimentation (e.g. Tarr 1926, Trowbridge 1917).

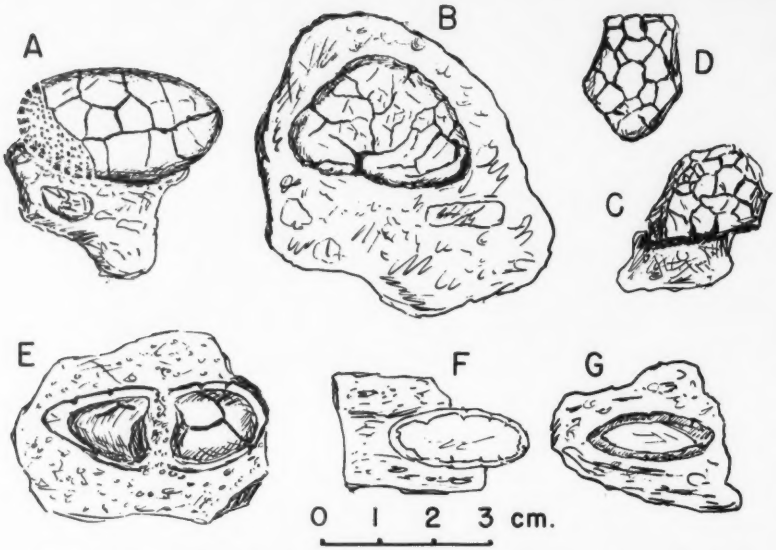

FIG. 4.—Different kinds of the chert pebbles from the conglomerate horizon in the upper part of the Oneota dolomite in SE¼ sec. 5, T. 26 N., R. 16 W. on the left bank of the Rush River, Wisconsin. A and B, rounded chert pebbles showing dehydration cracks. C, a part of brecciated chert pebble with strong cracks. D, small chert pebble of irregular form with mud-cracks. E and F, chert nucleus with dolomite coating (nucleus of E brecciated). G, dolomitic pebble with chert coating.

Moreover, the presence of diffusion banding in the chert pebbles suggests the syngenetic colloidal origin of the chert. The idea of a secondary silicification of primary dolomitic pebbles is untenable and the above described features clearly indicate separate sources of dolomite and chert pebbles.

The preservation of fossils in the siliceous parts of rock (and the black pigment in chert) also indicates an earlier period of silicification before destruction of the fossils (e. g. Twenhofel 1932, p. 715, Stauffer and Thiel 1941, pp. 57, 58).

There are still other observations which support syngenetic silicification. (a) Silicification as a result of surface weathering could not have taken place shortly after regression of the Oneota sea for, if that had happened, a great deal of silica would have to accumulate in the uppermost part of the sediment. However, it is most common in lower layers. Ulrich (Bain and Ulrich 1905, p. 27) believed that such cherts originated during periods of intraformational exposure which were marked by chert conglomerates. The fact that in the present area these conglomerates are most abundant in the upper part of the Oneota, far from the zone of maximum silicification, disproves this hypothesis. (b) The development of silicified zones near the surface and parallel to the slope were undoubtedly produced by later meteoric solutions. However, the zone referred to in (a) above is parallel to the stratification and furthermore, silicification may be observed also in drill cores taken more than 300 feet below the surface (Thwaites 1923, p. 543, table III). (c) Rush Valley is mainly a product of glacial and post-

glacial erosion and there has been insufficient time for such large-scale secondary silicification. (d) Moreover, there is no relationship between the silica aggregations and ground water channels. The amount of silicified rock which occurs as float on the slope is somewhat greater than that seen in the outcrops, but this is due to the greater resistance of chert to weathering and not to its primary occurrence (e. g. fig. 1B). Chert may also occur in vertical bluffs.

The rare chert concretions and layers are, therefore, syngenetic accumulations of colloidal silica which indicate the occurrence of more or less favorable conditions for the coagulation of silica during the time of the sedimentation of the dolomites. However, morphologically the most common forms of silicified rocks are the siliceous stromatolite colonies, which have elsewhere a tendency toward selective silicification (e.g. Bain and Ulrich 1905, Twenhofel and Thwaites 1919). It is probable, therefore, that the concentration of silica in these remains was dependent on the type of algal carbonate and also on conditions favorable for silica coagulation, caused by decomposition of organic matter. The same decomposition produced a reducing environment that led to the precipitation of iron in the form of black pigment and pyrite. Later oxidation of the pigment during the aging of the gel, developed the characteristic reddish color of the quartz crystals.

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FIGS. 1–6, SEPTEMBER, 1953

A STUDY OF POROSITY AND GRAIN RELATIONSHIPS IN EXPERIMENTAL SANDS[1]

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ABSTRACT

Fourteen samples, each of 50 grams, of well-sorted, moderately rounded, medium-grained St. Peter sand were artificially packed and cemented with Lakeside 70 cement. Thin and polished sections of the samples were prepared and studied to determine the original or pre-induration condition of such a sand with respect to (1) porosity, (2) average number of contacts per grain, (3) percentages of grains with given numbers of contacts, and (4) percentage of contact types.

These data will serve as a basis for determining the presence and extent of pore-space reduction in natural sandstones due to induration.

The investigation showed that natural sands similar in texture to those used in this study should have (1) a porosity of about 37 per cent; (2) 0.85 contacts per grain; (3) 46 per cent floating grains, 31 per cent grains with one contact, 16 per cent grains with two contacts, 6 per cent grains with three contacts, and 1 per cent grains with four contacts; and (4) 77 per cent tangential contacts, 17 per cent long contacts, and 6 per cent concavo-convex contacts. The investigation further suggests that the factors of porosity, average number of contacts per grain, and percentage of grains with given numbers of contacts are controlled primarily by sorting and packing while the percentage of contact types is a function of grain shape.

The difficulties encountered in measuring the properties of porosity and grain relationships in this study were due chiefly to the Lakeside 70 cement. Future experimental work of this kind will yield more satisfactory results if a bonding agent can be found that nearly equals the grains in hardness and will not flow or melt during the preparation of thin sections.

INTRODUCTION

The purpose of this study is to determine the original or pre-induration condition of some artificially packed and cemented sandstones with respect to (1) porosity, (2) average number of contacts per grain, (3) percentages of grains with given numbers of contacts, and (4) types of contacts between grains. To the writer's knowledge Taylor's (1949) data on a single experimental sand of randomly packed sand grains provides the only information of this type available for newly deposited, non-indurated sands.

The establishment and application of additional basic information regarding unconsolidated sands would aid in determining the extent of post-depositional change in naturally deposited sandstones. The need for such information has been brought out by the work of Taylor (1949), Manry (1949), Beaudry (1950), and Hays (1951) on the problem of pore-space reduction in sandstones. They measured in thin sections the number and type of contacts between grains and the porosity of natural sands of varying composition, texture, and post-depositional history, but for comparison with their data they did not have adequate information on sands as originally deposited (prior to induration).

To obtain this information experimentally it was decided to start with very well-sorted material of medium sand size and to hold the conditions of

[1] A dissertation submitted to the Graduate School of Arts and Sciences of the University of Cincinnati in partial fulfillment of the requirements for the degree of Master of Science, 1951.

The writer wishes to thank Dr. Gordon Rittenhouse, under whose guidance this thesis was written, for his helpful advice and criticisms. Appreciation is also expressed to the other members of the faculty of the Geology Department of the University of Cincinnati for their valuable suggestions and criticisms.

sphericity, roundness, and composition constant. Three classes of samples differing slightly in sorting and average size but otherwise constant were used. The data and conclusions obtained apply only to deposits with the same or similar textural characteristics of sorting, roundness, and shape, but the probable variation in other sands can be inferred to some extent.

For the present study 14 samples of disaggregated St. Peter sandstone were artificially indurated with molten Lakeside 70, and the porosity and grain relationships were studied in polished sections and thin sections. A total of 14 polished sections (one of each sample) and three thin sections (one of each class) were prepared and studied. Porosities of the indurated samples were obtained prior to sectioning by comparing the bulk volume of a given sample to the volume of its constituent grains. The purpose of this was to check the porosities determined from polished and thin sections and to determine the degree of experimental error in the laboratory investigation.

In regard to the original purposes expressed above, this investigation showed that in thin sections well-sorted, medium-size, competently indurated sand should have (1) an actual porosity of about 37 per cent; (2) an average of about 0.85 contacts per grain; (3) 46 per cent floating grains, 31 per cent grains with one contact, 16 per cent grains with two contacts, 6 per cent grains with three contacts, and 1 per cent grains with four contacts; and (4) 77 per cent tangential contacts, 17 per cent long contacts, and 6 per cent concavo-convex contacts due to original packing and grain shape. The average percentage of grain circumference in contact with other grains was not measured as carefully as the four above mentioned factors but appeared to be less than 5 per cent. The investigation further showed that there was very little variation in porosity, average number of contacts per grain, and types of contacts between grains within the sorting and average grain size ranges considered.

The present investigation needs to be expanded to include a series of samples of sands in which all of the above mentioned factors are controlled and can be varied as desired. Future research then should be a systematic investigation on the effects of sorting, grain size, sphericity, roundness, and composition, considered separately and in combination, on the porosity, average number of contacts per grain, percentage of grains with given numbers of contacts, and types of contacts between grains. To control the factors of roundness, sphericity, sorting, and composition, it will be necessary to study experimental sands. This means that packing will be artificial, thus natural sands (beach, bar, dune, etc.) must also be studied to determine the effects of natural packing.

PREVIOUS WORK

A review of the work done on pore space reduction in sandstones at the University of Cincinnati, 1948–1951

Taylor (1949) observed that the original porosity—*i.e.*, pore space plus interstitial cement—for some Mesozoic subgraywackes and feldspathic sands was appreciably less than might be expected. She approached the problem of pore-space reduction by (1) establishing criteria whereby processes that reduce porosity can be recognized in thin section and (2) determining the relationship of the number and type of grain contacts with depth of burial. Part of Taylor's results are reproduced in figure 1. From this figure it can be seen that (1) the average number of contacts per grain increases with depth of burial in a straight line relationship; (2) tangential contacts decrease with depth and were not observed below 6,832 feet; (3) long contacts increase from 38 per cent at 2,885 feet to 61 per cent at 5,000 feet, then decline to 45 per cent at 8,343 feet; (4) concavo-convex contacts increase from 10 per cent at 2,885 feet to 29 per cent at 7,000 feet, then decrease to 23

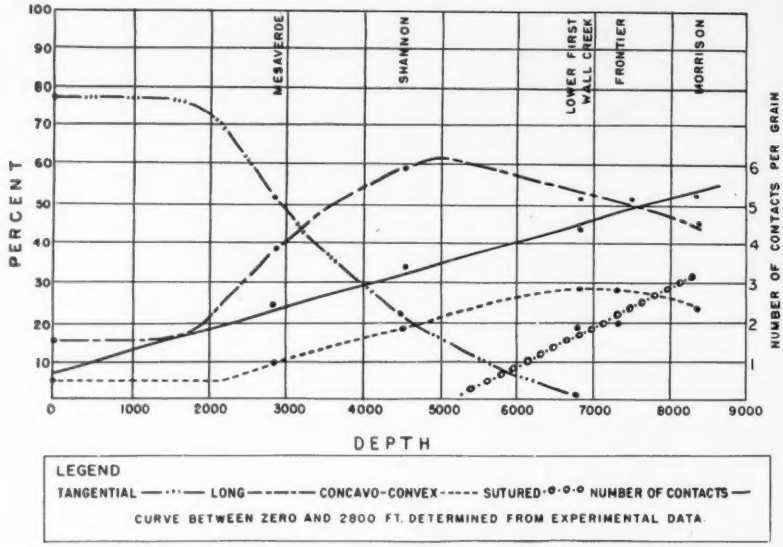


FIG. 1.—Graph showing number and types of contacts in Wyoming and experimental sands (after Taylor).

per cent at 8,343 feet; (5) sutured contacts increase from 19 per cent at 6,832 feet to 39 per cent at 8,343 feet.

A figure of 1.6 contacts per grain was obtained by Taylor for a randomly-packed experimental sand and agrees fairly well with the contacts per grain curve determined from the well-core samples and extrapolated to zero depth (fig. 1). This, however, might be misleading, since the total thickness of Cretaceous sediments overlying the shallowest Mesaverde sample may have exceeded 8,000 feet (Taylor, p. 5, 1949). Taylor believed that the number of long and concavo-convex contacts was due partly to packing and original grain shape and partly to the effects of compaction from pressure. Sutured contacts were entirely due to pressure, while tangential contacts are the result of original packing and grain shape. Taylor (1949, p. 27) concludes that:

"The number of contacts per grain, the presence of concavo-convex contacts and sutured contacts, and the crushing and yielding of micas, feldspars, and rock fragments, appear to be sound criteria for recognition of the effect of pressure on the reduction of porosity in sandstones."

Manry (1949, p. 30) found that in six Paleozoic orthoquartzites compaction had reduced the pore space from an assumed original porosity of 38 per cent to an average of 23 per cent. An additional reduction to an average of seven per cent was attributed to simple pore filling by chemical precipitation of cement. The number of contacts per grain in those quartzites varied from 1.2 to 3.1, considerably less than the maximum of 5.2 observed by Taylor. This may be due to (1) the different compositions of the rocks involved; (2) relatively early lithification of the quartzites, thus arresting pore-space reduction, due to pressure; or (3) shallower burial of the quartzites.

In the study of Pennsylvania sandstones from depths ranging from 8353 feet to 13,096 feet, Beaudry (1950) found porosities reduced to less than 9 per cent from an assumed original porosity of approximately 37 per cent. Some 60–65 per cent of this reduction he attributed to simple pore filling by quartz and carbonate cement that may have been introduced in solution after deposition, or a combination of introduced cement and solution of quartz at points of contact and re-deposition in adjacent pores (Waldschmidt, 1941). Beaudry believed that processes that caused the remaining 35–40 per cent of pore space reduction were (1) mechanical rearrangement, (2) crushing and bending of grains, (3) solution and plastic flow, and (4) replacement and recrystallization. The low average number of contacts per grain (from 2.1 to 3.6) and the relatively small amount of other effects of pressure in these sands as compared to Taylor's was attributed by Beaudry to (1) more resistant composition—high percentage of quartz grains, low percentage of rock fragments, and feldspars—and (2) early introduction of cement that filled part of the pore space and generally indurated the rock before great pressure was applied. Beaudry concluded that in his samples there was no relationship between (1) porosity and depth, (2) number of contacts per grain and depth, or (3) type of contacts and depth. There was, however, a relationship between the number of contacts per grain and composition in that the sample with the most contacts per grain had the largest percentage of calcite grains, and the sample with the fewest contacts per grain had the largest percentage of quartz grains.

Hays (1951) made a study of deeply buried sands of about the same age and composition as those observed by Taylor. His samples ranged in depth from about 13,000 to 21,000 feet. One of the purposes of Hays' work was to determine whether the average numbers of contacts per grain increased and types of contacts between grains changed with the depth of burial in rocks of the same age and same composition, as those studied by Taylor but buried more deeply. From 43 to 75 per cent of the original porosity of these sands was accounted for by simple pore filling, authigenic quartz, and remaining pore space. The rest of the original pore space had been eliminated by pressure effects. The average number of contacts per grain varied irregularly with depth from 1.7 to 2.2; Hays concluded that in his samples the number and types of contacts was not related to depth. Hays also noticed that the samples with the largest amount of carbonate had an abnormally high percentage of sutured contacts. This suggests that composition may have had a more important effect on the percentage of contact types than depth of burial. Pressure effects were thought to have been minimized by the early development of authigenic quartz which Hays termed "competent cement."

A review of the literature concerning porosity

Graton and Frazer (1935) have shown that porosity in aggregates of systematically packed and uniformly sized spheres varies from 26 to 49 per cent, depending on the geometrical arrangement of the spheres. In haphazard packing where the individual grains have no consistent relationship to one another, the minimum porosity would be greater than 26 per cent and the maximum unknown, yet conceivably greater than 49 per cent. In nature the method of packing is a combination of these two types and is termed random packing.

The porosity in such randomly packed sands is controlled by (1) method of deposition, (2) sorting, (3) grain shape, and (4) grain size. A discussion of these controlling factors follows.

(1) Under method of deposition, two main factors are to be considered; (a) whether or not material was deposited in water and (b) whether or not the medium of deposition is able to rearrange the

grains so that they occupy the most stable position possible.

Sand deposited in water will have a higher porosity than subaerially deposited sand because of the greater buoyancy of water, and because of the film of water that attaches itself to each grain on wetting. Trask's (1931, p. 272) experiments showed porosities from 45 to 47 per cent for medium to very fine sands (.500–.064 mm) deposited in water with no compacting overburden. Ellis and Lee (1919, p. 121) found that the average porosity for 36 samples of river valley fill (ranging in size from coarse sand to fine sandy loam) was 45.1 per cent. Frazer (1943, p. 936), working with coarser material (average grain size, 1.500 mm), obtained essentially the same results, experimentally, as Trask.

Frazer also did experimental laboratory work on dry and compacted (rearranged) sands and found that dry, loose sand had a porosity of about 41 per cent. With fine-grained, natural beach sands, Frazer found the porosity of wet sand to be 44.21 per cent and the porosity of dry sand to be 41.56 per cent. From the results obtained by these workers, it appears that sands deposited subaerially have about 3 to 6 per cent less porosity than those deposited in water. A further porosity reduction was accomplished in the experimental dry sand through compaction by jarring which rearranged the grains. In Frazer's work this reduction was approximately 4 per cent for rounded sands, and about 7–10 per cent for angular material. From this it appears that the porosity of a dry, compacted material ranging from uniformly-sized spheres to well-sorted, moderately round grains, would be equal to the porosity of dry, loose sand minus the amount lost to compaction by jarring (41 per cent minus 4 per cent equals 37 per cent). This size, sorting, and shape range would include many dune, beach, and marine sands.

(2) The effects of sorting on porosity can be quite complicated. Generally the porosity decreases as grains vary from a uniform size because (a) the finer grains tend to occupy voids between larger grains, and (b) the coarsest grains reduce porosity by occupying a volume that would otherwise be occupied by finer grains and voids.

Two other factors, according to Frazer's experimental results, work in the opposite direction and tend to increase porosity, but are of a lesser importance. First, small grains that are larger than the critical size of occupation as defined by Frazer (1935), tend to hold larger grains apart, and second, packing around the larger grains is looser than it would be if the grains were all the same size, because the larger grain surfaces have the same effect on packing as container walls.

Figure 2 shows some of King's (1898) experimental data with simple (closely sized) sands and mixtures of simple sands. From this it can be seen that:

a) well-rounded, well-sorted sands have porosities ranging from about 34 per cent for coarse sand to 38 per cent for fine sand (curve A, fig. 2).

(b) decreasing the sorting by mixing different proportions of two different sized sands causes porosity to decrease (curves B and C, fig. 2).

(c) the lowest porosity of about 25 per cent was obtained by a mixture of 60–70 per cent sand finer than .10 mm and 30–40 per cent well-sorted sand with average diameter of .48 mm. This porosity is about 12 per cent lower than the average for well-sorted, well-rounded, medium-sized sand (curve C, fig. 2).

From the experimental work done in this investigation, the addition of 8 grams each of .500 to 1.000 mm and .062 to .250 mm material to 84 grams of .250–.500 mm sized grains causes a porosity reduction of only 1.75 per cent.

(3) As used by Frazer, grain shape is a combination of sphericity and roundness. The results of experiments with spheres, natural sands, and crushed calcite, quartz, halite, and mica particles show that there is a decrease and then an increase in porosity as grain shape varies

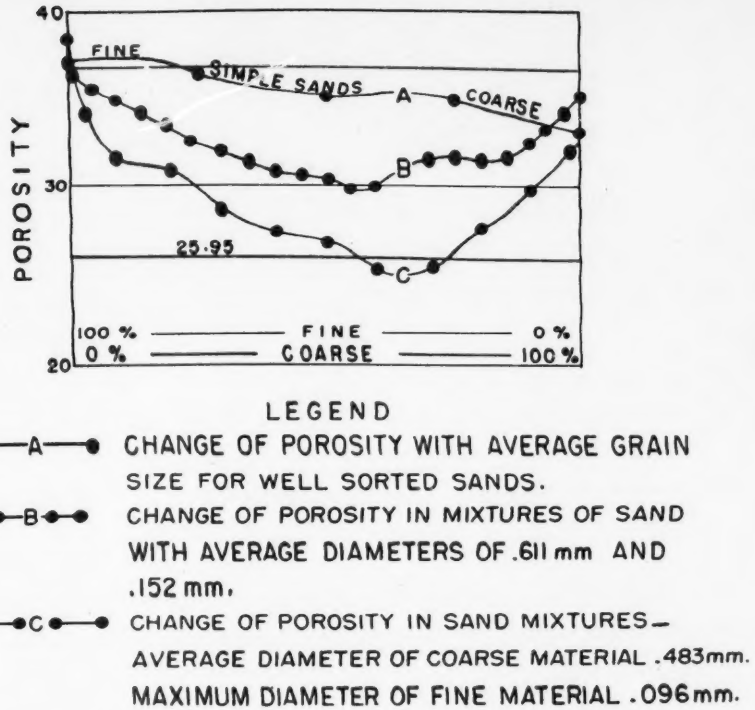


FIG. 2.—Variations in the percentages of pore space in various samples of simple sands and binary mixtures of simple sands (after King).

from spherical to platy. The minimum porosities were for grains that were "mildly and uniformly disc-shaped" (Frazer 1935, p. 938).[2] Porosity, then increased with decreasing sphericity and roundness until the maximum of about 90 per cent porosity was reached with crushed mica. Crushed quartz, halite, and calcite all had maximum porosities of about 50 per cent. Frazer attempted to keep the sizes of the various experimental materials constant by using grains passed through an 18 mesh sieve and retained on a 35 mesh sieve (average diameter 1.5 mm). Although Frazer was aware of the general effect of shape on the size of grains passed by sieves (Rittenhouse, 1943) he did not take it into consideration in his work. He apparently did not believe that the porosities he obtained would be appreciably affected.

(4) In the finer sediments (silts and clays) the average grain size would also affect porosity. The increase of friction, adhesion, and bridging with decreasing grain size tend to increase porosity. This factor is probably small among grains in the sand range.

It is interesting to note that the porosity of 37 per cent obtained by King

[2] Tickell and Hiatt (1938, pp. 1272–1274) found that aggregates of grains with a roundness of .82 have the lowest porosity.

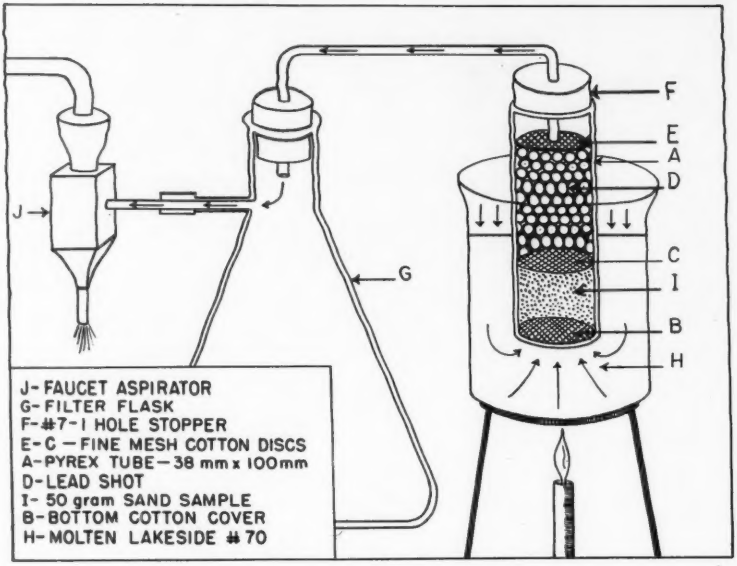


FIG. 3.—Apparatus employed for indurating sand samples.

(1899, p. 216) for well-rounded, simple (well-sorted) sands is in close agreement with that obtained by Frazer (1935, p. 936) and that this value is very close to the mean value between the maximum and minimum porosities of systematically packed, uniformly sized spheres. Of especial interest to the author is the fact that this porosity agrees closely with that obtained in the experimental work of this study.

EXPERIMENTAL PROCEDURE

St. Peter sand was used in all experiments to insure uniformity of composition, size, sphericity, and roundness. The procedure employed is as follows:

1. Preparing samples.—Mechanical analyses were made of three 100-gram samples of the graded St. Peter sand. The results of the three test samples were averaged and plotted as a cumulative (per cent by weight) curve from which the Trask sorting coefficient was found to be 1.109. This indicates a well-sorted sand.

Three classes of samples of the sand were then obtained as follows:

Class I: Six 50-gram samples, passed through the 32-mesh (.500 mm) sieve and retained on the 35-mesh (.420 mm) sieve;

Class II: Four 50-gram samples of the unsieved graded St. Peter sand;

Class III: Four 50-gram samples passed through the 32-mesh (.500 mm) sieve and retained on the 60-mesh (.250 mm) sieve.

2. Cementing samples.—The samples were cemented by drawing molten Lakeside 70 up through the packed samples. Due to the high viscosity of the Lakeside 70, capillary action was insufficient and therefore partial vacuum was applied to induce saturation (fig. 3).

Sections of glass tubing (a, fig. 3), 4 inches long and 38 mm in diameter were

used for forms or molds for the cementing process. The tubes were lined with aluminum foil to facilitate removal of the cemented samples and were covered on one end by tightly drawn cotton cloth (b, fig. 3) that was affixed to the tube by rubber bands and plastic cement. The tube was placed on a smooth glass base plate and the thoroughly mixed 50-gram sand sample was then poured into it. Compaction was obtained by tapping the tube and then gradually applying a force of about 25 pounds by means of a smooth based cylinder slightly smaller than the interior diameter of the containing tube. A porous cloth disk (c, fig. 3) was placed on the sample and the remainder of the tube was filled to within about one-half inch of the top with uniformly sized lead shot (d, fig. 3). Another porous disk (e, fig. 3) was inserted and the tube sealed with a no. 7 one-hole rubber stopper (f, fig. 3) which fitted firmly on top of the lead shot. The system was connected through the one-hole stopper to a filter flask (g, fig. 3). The cloth-covered end of the containing tube was immersed in molten Lakeside 70 (i, fig. 3) as vacuum developed in the filter flask. From three to five minutes were required to saturate 50–75 per cent of the sand. Care was taken not to cement any of the lead shot to the sand because separation of the shot and sand resulted in damage to the sample. When it was estimated that enough cement had penetrated the sample, the vacuum aspirator was disconnected and the cloth-covered end of the containing tube was immediately chilled in cold water to prevent the still molten Lakeside 70 from draining out of the sample. The cement solidified after 10 to 15 minutes of cooling at room temperature.

3. Preparing the polished sections.—When the samples had hardened, the lead shot and uncemented sand were poured off and separated by sieving. The weight of cemented sand was determined by deducting the weight of uncemented sand from the total amount of sand used (50 grams). The consolidated sample was removed from the containing tube and weighed in air and in water. Sections one-fourth inch thick were cut parallel to the flat bottom surface. This newly cut surface was ground smooth, using carborundum on glass plates, and then polished on a lap.

4. Laboratory determination of porosity.—The general formula used for porosity in per cent of bulk volume was

$$P = \frac{V_b - V_g}{V_b} \times 100$$

Where

P = porosity in per cent of bulk volume,

V_b = bulk volume of sample, determined by subtracting the weight of the specimen suspended in water from its weight in air (the difference representing the weight of water displaced which is equal in volume to V_b when density of water equals 1).

V_g = volume of grains in aggregate, determined by dividing the weight of cemented sand by 2.65 (2.65 is the specific gravity of quartz).

OBSERVATION PROCEDURES

The 14 polished sections were mounted on glass plates and studied by reflected light under a metallographic microscope. The magnification was about 20 diameters. For each polished section, the porosity in one hundred fields was measured by counting the number of micrometer ocular divisions of cement. This method is a modification of that described by Johannsen (1914, p. 291–293).

For each polished section the number and type of contacts per grain of one hundred grains were observed. Only the grain in the center or nearest the center of each field was considered. The number of contacts varied from zero (floating grains) to five. The contacts were classified as (1) tangential, (2) long, or (3) concavo-convex. These terms were defined by Taylor (1949, p. 14–17) as follows: tangential contacts are those that appear

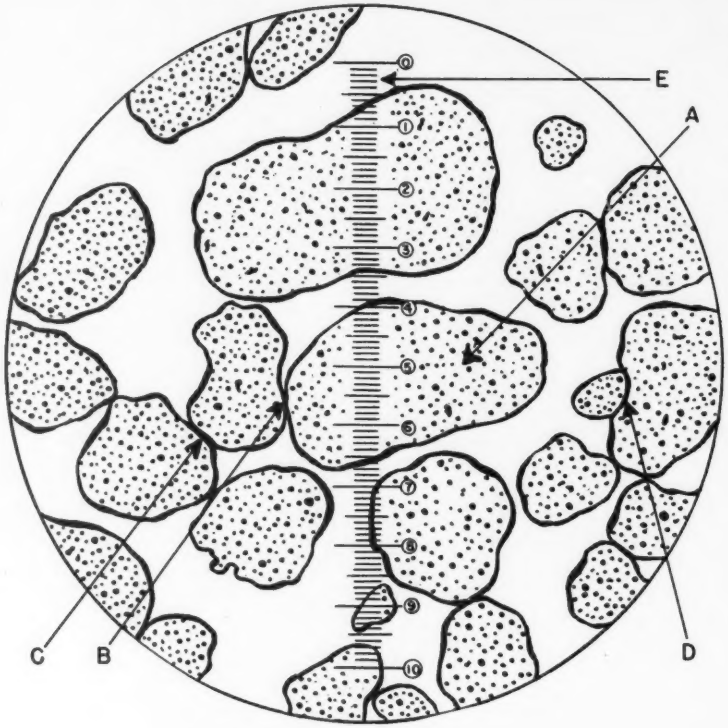


FIG. 4.—Polished section of experimental sand in reflected light (X75). Porosity in per cent is represented by the number of scale divisions in unstippled areas.

as a point in the plane of the section; long contacts appear as a relatively straight line; and concavo-convex contacts as a curved line. Sutured contacts, the fourth type defined by Taylor, and believed by her to result from great pressure, were not observed in this investigation.

Figure 4 shows a typical field of polished section viewed in reflected light. With the aid of the micrometer ocular, the porosity in this field was determined to be about 32 per cent. The observed grain (A) has one contact and it is tangential, at (B). Long (C) and concavo-convex (D) contacts are also shown in the field but they would not have been counted because they are not on the

TABLE 1—BASIC DATA

			POROSITY			NUMBER AND DISTRIBUTION OF CONTACTS PER GRAIN							PERCENTAGES OF CONTACT TYPES		
		SAMPLE	POROSITY WGHT & VOL.	POROSITY POL. SEC.	POROSITY DIFF.	AVG. NO. CONTACTS PER GRAIN	PERCENT OF GRAINS WITH GIVEN NUMBERS OF CONTACTS						TANGENTIAL	LONG.	CONCAVO-CONVEX
							0	1	2	3	4	5			
POLISHED SECTIONS	CLASS I .420 mm.–.500 mm.	A	38.2	30.5	7.7	1.18	32	31	26	9	2	0	73	22	5
		B	39.0	31.3	7.7	1.09	29	38	28	5	0	0	68	29	3
		C	35.4	26.5	8.9	1.06	27	44	25	4	0	0	71	22	7
		D	37.2	34.1	3.1	1.31	30	29	25	13	2	1	--	--	-
		E	37.3	31.0	6.3	1.26	24	37	29	9	1	0	--	--	-
		F	----	33.0	---	1.20	19	47	25	6	3	0	--	--	-
		AVG.	37.4	31.1	6.3	1.20	27	38	26	8	1	0	71	24	5
	CLASS II GRADED ST PETER	G	36.1	30.9	5.2	1.08	28	43	22	7	0	0	73	18	9
		H	36.1	32.8	3.3	1.00	29	51	12	8	0	0	82	12	6
		I	35.8	28.1	7.7	1.38	23	41	15	17	4	0	81	11	8
		J	35.8	30.7	5.1	1.52	18	38	25	12	7	0	75	18	7
		AVG.	36.0	30.6	5.4	1.28	24	43	18	12	3	0	78	15	7
	CLASS III .250 mm.–.500 mm.	K	39.1	30.7	8.4	1.31	22	39	29	6	4	0	84	12	4
		L	37.1	28.8	8.3	1.42	24	31	29	12	3	1	88	10	2
		M	37.4	29.6	7.8	1.47	21	29	34	15	0	1	83	11	6
		N	37.1	29.8	7.3	1.51	18	31	35	14	2	0	83	10	7
		AVG.	37.7	29.7	8.0	1.43	21	32	32	12	2	0	84	11	5
	TOTAL AVG.		37.1	30.5	6.6	1.28	24.4	37.2	25.4	11	2	0	78	16	6
THIN SECTIONS	CLASS I	D	37.2	44.3	7.1	0.21	81	17	2	0	0	0	80	15	5
	CLASS II	H	36.1	44.7	8.6	0.38	67	28	5	0	0	0	76	16	8
	CLASS III	L	37.1	44.4	7.3	0.51	61	29	8	2	0	0	73	21	6
	TOTAL AVG.		37.1	44.5	7.4	0.37	69.7	24.7	5	.6	0	0	76.3	17.3	6.4

grain which is at or nearest to the center of the field.

The three thin sections were studied by transmitted light and a petrographic microscope. The method of sampling and the type of observations were the same for thin sections as for polished sections. As will be shown, the two methods of observation yielded somewhat different results.

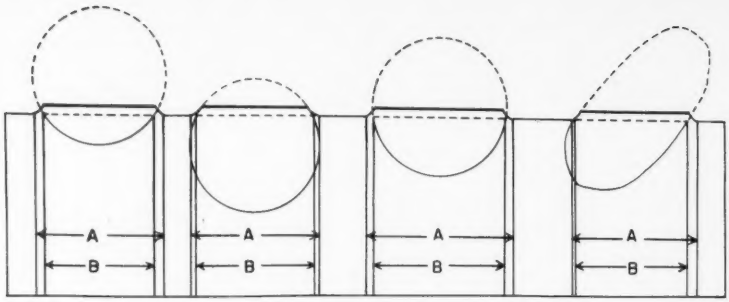
DISCUSSION OF DATA

Polished section

Porosity.—The purpose of determining the porosities of the samples by weight and volume was twofold: first, to determine the experimental error of packing and cementing the sands, and second, to serve as a basis of comparison for the porosities obtained microscopically from polished and thin sections.

The porosities determined from polished sections are consistently smaller than those obtained by weight and volume measurements (table 1). In class I the differences averaged 6.8 per cent; in class II, 5.3 per cent; and in class III, 8.0 per cent. For all 14 samples the average was 6.7 per cent lower. This discrepancy appears to be due largely to the difference in hardness of the quartz grains (7) and the Lakeside 70 cement (2+) which caused the grains to stand out in relief on the polished surface. As shown in figure 5, this will reduce the amount of pore space as measured in the polished section.

It is possible that the transparency of the cement, which would allow light to be reflected from part of the grain below the surface of the section, may also be a factor. Non-random orientation of the grains could not have caused the difference, though it may have had a slight effect.



A—APPARENT GRAIN DIAMETER IN PLANE OF CEMENT

B—ACTUAL GRAIN DIAMETER IN PLANE OF CEMENT

FIG. 5.—Idealized cross-section of polished section surface.

Number of contacts per grain in polished section.—The average number of contacts per grain for the three classes of sand studied was found in class I to be 1.2; in class II, 1.2; and in class III, 1.4. Samples from each class were re-examined to determine whether the difference of 0.2 contacts per grain was caused by a difference in the samples or by observational bias. Under more carefully standardized procedures of observation, a closer agreement between class III and the other two classes was observed. It was concluded that (1) the differences in the average number of contacts per grain between the classes studied in this investigation were due primarily to sampling and experimental errors rather than to differences in sorting and average grain size and (2) well-sorted, medium-sized, non-indurated sand should have about 1.2 contacts per grain when observed in polished sections. Poorer sorting would probably cause the average number of contacts per grain to be larger.

In reflected light the cement (white, fig. 4) and the grains (stippled, fig. 4) are separated by a black band. This black band was considered to be a part of the grain. Since the relief on the polished surface widens the bands and thereby increases the apparent number of contacts, as well as reducing porosity (fig. 5), the resulting averages are too high but can still serve as a maximum expected value for the type of sand here considered.

The number of contacts per grain can be considered in terms of the percentages of grains with a given number of contacts. These data are given in table 1 and are represented graphically in figure 6; in polished sections (a) there were no grains observed with more than five contacts, (b) 98 per cent of the grains observed had fewer than 4 contacts, (c) grains with 1 contact occurred most frequently—37.2 per cent, (d) floating grains and grains with 2 contacts occurred at about the same frequency—24.4 per cent and 25.4 per cent respectively, and (e) 11 per cent of the grains had 3 contacts. Deviations from this in natural sands observed in the same manner would indicate degree of compaction and/or difference in sorting. Thus, if the sorting of a sand similar in texture and composition to the sand used in this investigation can be determined either by disaggregation and sieving or thin section mechanical analysis (Krumbein, 1935), compaction would be suggested by (a) presence of grains with more than 5 contacts, (b) more than 2 per cent of the grains having 4 or more contacts, (c) grains having 2 or more contacts oc-

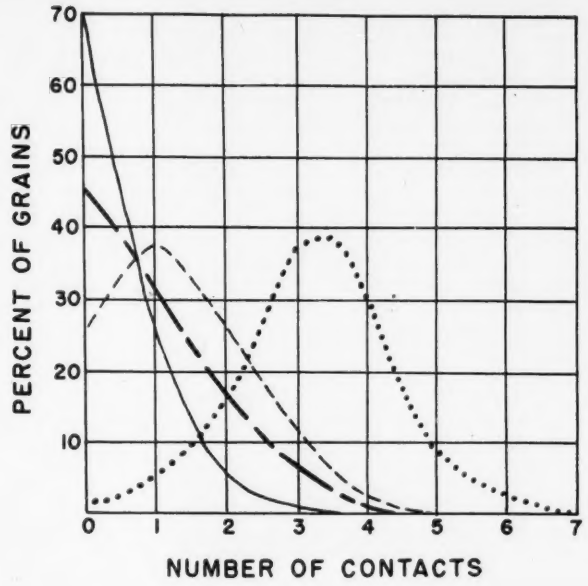


FIG. 6.—Comparison of percentages of grains with given number of contacts as obtained from thin and polished sections of experimental and natural sands.

curring most frequently, and (d) reduction or disappearance of floating grains. The greater the deviation from experimental results, the greater the confidence that compaction has occurred.

In figure 6, the dotted curve represents the distribution of grains with given numbers of contacts for Beaudry's deeply buried (8,000 to 13,000 feet) sands and shows how much compaction will cause this curve to differ from the same kind of curve for uncompacted material (heavy dashed curve).

Types of contacts in polished sections.—As previously mentioned, Taylor (1949) has classified grain contacts on the basis of their appearance in thin sections. The types of contact described by her were tangential, long, concavo-convex, and sutured. Sutured contacts were not observed in this investigation. She believed that tangential contacts can result from original packing and grain shape and in part from post-depositional pressure effects.

The purpose of determining the types

of contacts between grains in this investigation was to establish the percentages of each type of contact due to original packing and grain shape. This would serve as a basis of comparison for determining the degree of compaction in buried natural sands whose textures and compositions were similar to those of the experimental sands.

Since the contact types graded into one another, fairly large differences in the percentages of each type from one sample to another were observed. Because of these variations no clear cut relationships of contact types to sorting or average grain size were discernible within the sorting and average grain size range examined. The percentage range of the contact types was tangential, 68 to 88 per cent; long, 10 to 29 per cent; concavo-convex, 2 to 9 per cent. However, by averaging the percentages of contact types for all the samples, the proportion of contact types in polished sections of well-sorted, medium-sized, non-indurated sands was found to be tangential, 77 per cent; long contacts, 17 per cent; and concavo-convex contacts, 6 per cent.

THIN SECTIONS

Since thin sections have been and probably will be used in studies of pore-space reduction in natural sandstones, the writer attempted to convert the results of this investigation as determined by polished section into terms of thin sections. Thin sections were made from one sample of each class and studied in the same manner as the polished sections, except that transmitted light and a petrographic microscope were used.

The porosities as measured in the three thin sections were between 44 per cent and 45 per cent. This was from 7 per cent to 8 per cent higher than porosities determined by weight and volume measurements and from 14 to 15 per cent higher than those determined in reflected light. The average number of contacts per grain as measured in thin sections was correspondingly low, averaging 0.4 contacts per grain for the three samples examined. The percentages of grains with given numbers of contacts were: floating grains, 69 per cent; grains with one contact, 25 per cent; grains with two contacts, 5 per cent; and grains with three contacts, 1 per cent. The percentages of contact types measured in thin section were all within 2 per cent of those measured in polished section. The averages were, tangential, 76 per cent; long, 17 per cent; and concavo-convex, 5 percent.

Because the porosity as measured in thin sections greatly exceeds that existing in the sample as originally packed and cemented, some change appears to have occurred during the preparation of the thin sections. Some of the changes that might have caused the observed porosity increase and average number of contacts per grain decrease are:

(1) plucking of grains during the grinding process.

(2) spreading of the sample when mounted on the slide prior to grinding or when cover glass was added.

(3) spreading of sample during grinding process due to softening of cement by the heat generated by grinding.

Plucking of the grains would have an important effect in increasing porosity, but would be much less important in causing a decrease in the average number of contacts per grain. By looking at the slides without cover glasses under a binocular microscope, it was definitely established that some plucking had occurred. It is not believed, however, that this was the major factor causing the increased porosity. Because of the difference in porosity it would appear that no direct comparison could be made between thin section and polished section data. An actual comparison of thin and polished section data (table 1), however, shows that there is a marked similarity in the percentages of contact types, even though the data obtained for porosity, average number of contacts per grain, and percentages of grains with a given number of contacts were quite different. This suggests that the percentages of

contact types were independent of porosity, average number of contacts per grain, and percentages of grains with a given number of contacts. Perhaps the latter three factors were controlled primarily by sorting, packing, and apparent grain size while the percentage of contact types was primarily controlled by grain shape (sphericity and roundness).

In the case of thin sections, particularly of fine-grained sediments, the overlap of the grains due to the thickness of the section would result in higher percentages of long and concavo-convex contacts and lower percentages of tangential contacts than would be found on a plane surface. Grain overlaps in thin sections would also (a) reduce porosity, (b) increase the average number of contacts per grain, and (c) increase the percentage of grains that are in contact with other grains (or reduce the percentage of floating grains). These factors were not considered very important in this investigation because the average grain diameter of the material used was more than ten times as great as the thickness of the sections.

It would seem that thin sections of natural sands requiring impregnation would be subject to the same changes as those that occurred in these experimental sands. This means that porosity obtained from thin sections of impregnated (natural) sand may be too high and that the average number of contacts per grain may be too low. The percentages of grains with a given number of contacts would also be in error in that (a) the number of floating grains would be too high and (b) the percentages of grains with any other number of contacts would be too low. The percentages of contact types, however, would probably be essentially correct.

Implications

The four factors obtainable from thin and polished sections of sands, that aid in determining degree of compaction are (1) porosity, (2) average number of contacts per grain, (3) percentages of grains with given numbers of contacts, and (4) proportions of the various types of contacts. For reasons already given, the polished and thin section data concerning the first three of these factors are widely divergent and do not (except for item 4) in themselves represent the values that would be obtained by a similar thin section analysis of a well-indurated natural sand or an ideally impregnated experimental sand. It is suggested that such a thin section analysis would not be as subject to the errors introduced by differential hardness, as was the case with polished sections, or to the errors caused by spreading of the sample as observed in thin sections of artificially cemented sands. An attempt is here made to establish tentative values for the average number of contacts per grain and the percentages of grains with given numbers of contacts that should be observed in undisturbed thin sections of well-sorted, medium-sized, non-indurated sands. These values for the average number of contacts per grain and percentages of grains with given numbers of contacts were obtained on the basis of the following assumptions:

1) that the porosity of a sand as measured in an ideal thin section and polished section will be essentially equal to the porosity of the same sand as obtained by weight and volume measurements.

2) the values for porosity, average number of contacts per grain, and percentages of grains with given numbers of contacts will vary as thin and polished sections vary from an ideal condition to that condition in which they were observed in this investigation.

If these assumptions are correct, the average number of contacts per grain and percentages of grains with a given number of contacts are easily obtained by simple proportions and are:

1. Average number of contacts per grain	.85
2. Floating grains	46%
Grains with one contact	31%
Grains with two contacts	16%
Grains with three contacts	6%
Grains with four contacts	1%

The expected porosity for an ideal thin section of well-sorted sand would be 37 per cent, and the percentages of the types of contacts would be the same as those obtained from the thin and polished sections—that is, tangential, 77 per cent; long, 17 per cent; and concavo-convex, 6 per cent.

It must be remembered that these figures were not obtained by actual observation of ideal thin sections and hence are subject to error. It is believed, however, that these figures are of the proper order of magnitude and appear to be the best values now available for use in studying pore-space reduction and compaction of sandstones.

In figure 1, the curves obtained by Taylor for average number of contacts per grain and percentages of tangential, long, and concavo-convex contacts are extended to zero depth on the basis that unburied or uncompacted sands should have about .85 contacts per grain, 77 per cent tangential contacts, 17 per cent long contacts, and 6 per cent concavo-convex contacts.

CONCLUSIONS

Four of the measurable properties that can be used to determine the presence or magnitude of post-depositional change in sands are (1) porosity, (2) average number of contacts per grain, (3) percentages of grains with given numbers of contacts, and (4) percentages of contact types. It is believed that items (1), (2), and (3) are closely related and that variations in one will be attended by variations in the other two. The two most important factors that can cause such variation are compaction and changes in sorting. In order to use these factors for determining compaction, the sorting or effects of sorting must be known for the material in question.

The following conditions can indicate compaction if observed in a thin section of a competently indurated or impregnated buried natural sandstone whose texture and composition were similar to those of the sand used in this investigation: actual porosity less than 37 per cent, average number of contacts per grain in excess of .85, less than 46 per cent floating grains, and presence of grains with more than five contacts. Some variation in these values can be caused by small differences in texture and composition in the sand or by differences in the sampling and measuring procedures. Thus, the important thing to consider to determine compaction is the magnitude of the differences. For instance, if the data from a thin section of a well-indurated natural sand, similar in texture to the sand used in this study, had a porosity of 30 per cent and an average of 1.0 contacts per grain, compaction would not definitely be indicated but may have occurred. However, if this same textural type of sand should show a porosity of 20–25 per cent or less and 2 or more contacts per grain, compaction is definitely indicated.

Conversely, if a thin section of a competently indurated natural sand had a porosity greater than 37 per cent, average number of contacts per grain less than .85, more than 46 per cent floating grains, and the absence of grains with 3 or more contacts, a spreading of the grains would be indicated rather than compaction. This might be caused by an early introduction of cement (prior to compaction) that tended to force the grains apart.

In moderately or poorly sorted, non-indurated sands, the expectable variation in porosity, average number of contacts per grain, and percentages of grains with given numbers of contacts can be determined experimentally. This can be done by examining samples of poorly-sorted material but similar in other respects to the material used in this investigation and comparing the values thus obtained to the values obtained for well-sorted material in this study.

The proportion of contact types (item 4) would also indicate compaction if, under given conditions of roundness and sphericity, the percentage of tangential contacts was lower and the percentages of long and concavo-convex contacts were

higher than found in this study. If the proportions of contact types is independent of sorting and dependent on grain shape, as this study suggests, they will be more useful than porosity, average number of contacts per grain, or percentages of grains with a given number of contacts in determining compaction in sands in which the sorting is unknown.

To experimentally determine the limits of variation for the percentages of contact types in non-indurated sands, one would have to control the properties of sphericity and roundness and examine samples through as large a range of these properties as possible. There are four end conditions of sphericity and roundness to consider, and each may have its own characteristic proportion of contact types. These conditions are (1) high sphericity, high roundness (spherical grains), (2) high sphericity, low roundness, (3) low sphericity, high roundness, and (4) low sphericity, low roundness. Tangential contacts, probably, would be at a maximum in case (1) while long contacts probably would be at a maximum in case (4), particularly if cleavage and/or fracture controlled the shape of the grains. The relation of concavo-convex contacts to roundness and sphericity is not clear, but probably would be developed most abundantly in case (3). The material used in this investigation would be intermediate to these four extremes but closest to cases (1) and (2) (high sphericity, moderate roundness).

The workers concerned with the problem of pore space reduction in sandstones have assumed that well-sorted, undisturbed, uncompacted sands should have considerably less than 2 contacts per grain, and porosities between 35 and 40 per cent. The results of this investigation confirm these assumptions.

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FIGS. 1–4, SEPTEMBER, 1953

TETRAHEDROID PEBBLES

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ABSTRACT

Shore gravels of Pleistocene Lake Bonneville in Great Salt Lake Valley, Utah, have yielded unusual pebbles which are, in shape, variants on the fundamental tetrahedron. Field investigations of stream channels, alluvial fans, and talus slopes in the canyons of the nearby Wasatch Mountains have shown that these distinctive pebbles originate as corner fragments broken from rhombohedral or sub-cubical joint blocks tumbling down from highly jointed bedrock outcrops onto talus slopes. It is suggested that the shape of such fragments renders them quite resistant to any appreciable distance of stream transportation. On the basis of these observations, it is believed that the occurrence of appreciable numbers of tetrahedroid pebbles in gravels and conglomerates strongly indicates the non-marine origin of such rock units.

INTRODUCTION

The present paper reports the results of the first of a series of investigations of the effects of original particle shape on the ultimate shape of pebbles occurring in coarse-grained non-marine clastic sediments. These studies are in progress as part of a long-term program of research on the sediments of Pleistocene Lake Bonneville and its predecessor lakes in Great Salt Lake Valley, Utah. The occurrence of such widely varying sedimentary units as offshore bars, spits, alluvial fans, beach gravels, deltas, mudflows, and stream channels makes the region an ideal field laboratory for studies of the processes and products of non-marine sedimentation. Also, the abundance of coarse clastics in these units makes them ideal for the investigation of pebble shapes, since the source areas of the sediments are still accessible in the valleys of the streams issuing from the nearby Wasatch Mountains.

The writer wishes to express his thanks to Robert R. Lankford for assistance in the field and laboratory, and to Professor Ray E. Marsell of the Department of Geology of the University of Utah for many helpful suggestions in preparation of the manuscript.

PREVIOUS WORK

In the literature of sedimentation, there are surprisingly few references to the effects of original fragment shape on the ultimate shapes of pebbles and cobbles. Wentworth (1922) recognized the importance of the weathering processes in producing fragments of distinctive shapes, and the importance of the shape of the original rock fragment in determining ultimate pebble shape. He suggested the need for further detailed work on this phase of the problem. Tester (1931) states:

> "The writer is convinced by his observations on the shapes of pebbles and sand grains gained from field and laboratory studies that the original shape of the rock or grain when it is first subjected to abrasion is a primary control on the ultimate shape."

To the best knowledge of the present writer, no previous work has been reported on the tetrahedroid as a distinctive pebble shape, although Wentworth (1919), Cox (1927), and Tester (1931) in discussing techniques of measuring roundness and shape of pebbles, illustrate particles of triangular outline, which, in three dimensions, may be tetrahedroid in shape. Krumbein (1940) illustrates by

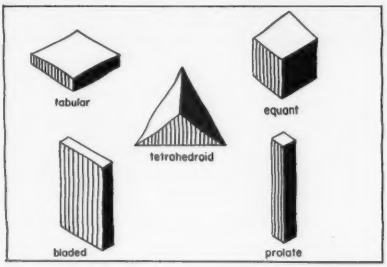

FIG. 1.—Comparison of tetrahedroid pebble with Zingg's classification of fundamental pebble shapes.

photograph some of the pebbles of the flood gravels of San Gabriel Canyon, California; and in the photographs the writer observed that tetrahedroid pebbles occur in an approximate ratio of 1 to 25 to other pebble shapes.

Wentworth (1922), in describing the pebble shapes of a beach gravel on Nantasket Beach, Massachusetts, shows a beach gravel containing a high incidence of what appear to be distinct, well-developed tetrahedroid pebbles.

NATURE OF THE TETRAHEDROID PEBBLE

In the course of field and laboratory studies of the shore gravels of Lake Bonneville, many pebbles were observed which in shape represent variations on the fundamental geometric tetrahedron. They are four-sided, but exhibit a wide variation in interfacial angles, and in face areas. Since they are similar to, but not identical with the true geometric form of the tetrahedron, they are here designated as *tetrahedroid pebbles*. Zingg's classification of fundamental pebble shapes, as illustrated by Pettijohn (1949), does not show any fundamental pebble shape class to which the tetrahedroid could belong. Figure 1 shows a comparison of the tetrahedroid pebble shape with the tabular, bladed, equant, and prolate classes as described by Zingg. It will be noted, however, that a corner fragment from any of the above fundamental shapes would be tetrahedroid in shape.

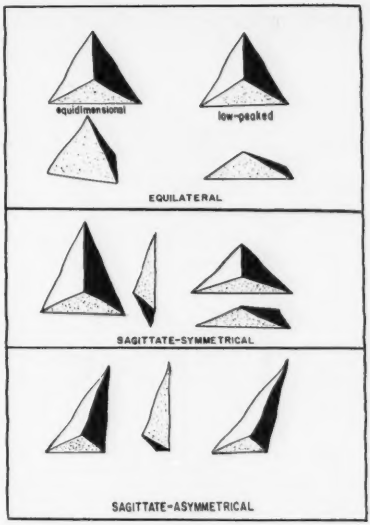

FIG. 2.—Shape classification of tetrahedroid pebbles (for purposes of clarity, rounding is not shown).

The specimens of tetrahedroid pebbles thus far studied range in size from $\frac{3}{8}$ inch to over 8 inches in maximum dimension, and may be grouped into the following three general shape classes, based upon their triangular outlines when viewed in plan, the pebbles resting on the base, or largest facet (see fig. 2):

1. Equilateral
   a. low-peaked
   b. equidimensional
2. Sagittate or isosceloid (symmetrical)
3. Sagittate asymmetrical

The sagittate forms, both symmetrical and asymmetrical, are far more common in the gravels studied than are either of the two sub-types of the equilateral tetrahedroid. Although the equidimensional tetrahedroids are the least common, they become more abundant in the smaller pebble sizes.

Lithologically the pebbles consist largely of fragments of the Nugget quartzitic sandstone, and the Twin Creek

limestone, both of Jurassic age, which crop out in the central Wasatch Mountains immediately east of Great Salt Lake Valley. Lake Bonneville gravels in the northern portion of the valley have yielded abundant tetrahedroid pebbles derived from nearby outcrops of lower Paleozoic limestones.

ORIGIN AND DEVELOPMENT OF TETRAHEDROID PEBBLES

In an attempt to explain the origin of the tetrahedroid pebbles which were found so commonly in the shore gravels under study, field investigations were made of the recent subaerial and fluvial sediments in the lower portion of Parley's Creek Canyon, eastern Salt Lake County, Utah. This valley was chosen for study because the Lake Bonneville shore gravels exposed near the mouth of Parley's Creek Canyon contained a considerable number of the pebbles in question. The steep walls of the canyon have many excellent exposures of the Nugget sandstone and Twin Creek limestone, with well-developed talus slopes occurring below the outcrops.

The following field observations in Parley's Creek Canyon are considered significant to the origin of the tetrahedroid pebbles:

1. The Nugget sandstone has a well-developed rhomboidal pattern of intersecting, closely spaced joints.
2. Close inspection of the fragments composing the talus below the Nugget outcrops showed a predominance of rhombohedral and subcubical joint blocks, with some wedge-shaped fragments produced by a third, weaker joint system.
3. The talus material also contained numerous tetrahedroid fragments, as well as many rhombohedra whose corners had been broken off. The incidence of tetrahedroid fragments markedly increased toward the base of each talus slope studied.
4. Exposures of recent channel fill and stream channel gravels three miles upstream from the mouth of the canyon yielded rhombohedral fragments and tetrahedroid pebbles, slightly rounded by stream transportation.
5. Exposures of near-recent channel fill immediately upstream from the mouth of the canyon yielded fewer tetrahedroid pebbles, but the specimens were somewhat more rounded than those found a few miles upstream.
6. Lake shore gravels near the mouth of Parley's Creek Canyon yielded only a few tetrahedroid pebbles. These specimens were well-rounded and had all but lost their distinctive tetrahedroid shape.

Figure 3 graphically summarizes the characteristics of the pebbles found at the localities described above, and demonstrates the progressive rounding of the pebbles downstream.

On the basis of the specimens thus far studied, and on the basis of field observations described above, it is here suggested that the tetrahedroid pebble shape is initiated when rhombohedral, equant, or subtabular joint fragments of resistant rock become dislodged and fall from the outcrop, and that the pebbles are originally fragments chipped or broken from the corners of such blocks during their rapid descent of the talus slope. Figure 4a shows a rhombohedral joint fragment, with planes of fracture or auxiliary joint planes intersecting the corners of the rhombohedron at varying angles. Figure 4b shows the same joint block, with the corner tetrahedroid fragments "exploded" away from the block. The equidimensional tetrahedroid fragment is believed to be derived from fragments whose corner angles are approximately 90 degrees.

It is suggested that auxiliary control of the fracturing of the rhombohedra by weaker joints is of secondary importance in deriving the tetrahedroid corner fragments. In limestones and sandstones characterized by strong cleavage along bedding planes, or by bedding planes more closely spaced than the spacing of

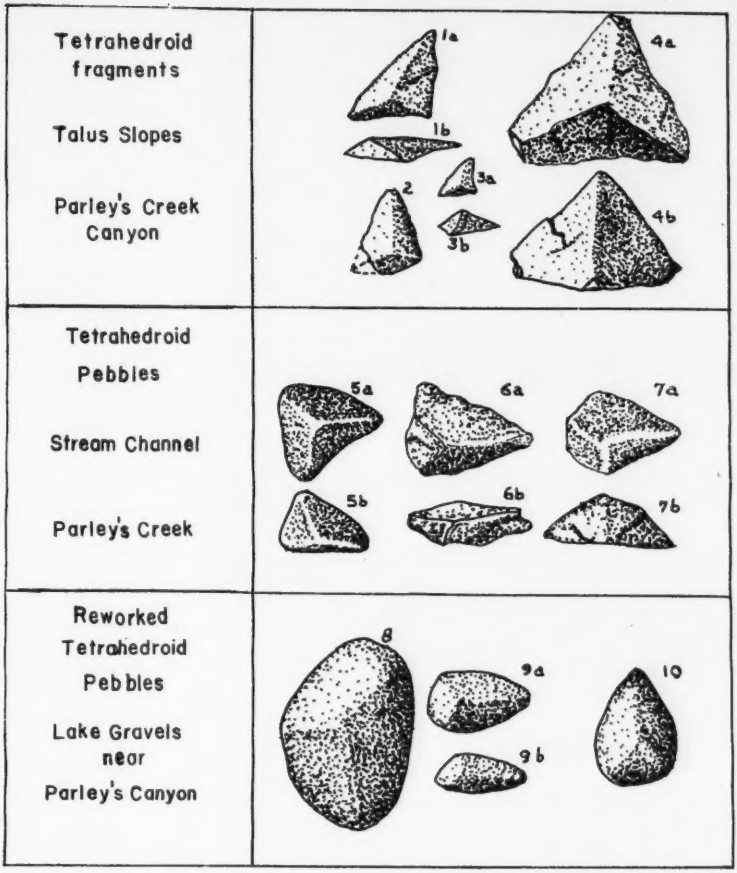

FIG. 3.—Tetrahedroid fragments and pebbles from talus slopes, stream gravels, and lake shore gravels in the vicinity of Parley's Creek Canyon, showing progressive rounding of fragments with transport.

the joints controlling the rhombohedral or subcubical shape of joint blocks, there is less tendency to develop recognizable tetrahedroid corner fragments during gravity transport from outcrop to talus slope. The rhombohedral joint blocks must be rather large, in order to have enough momentum to strike against other fragments with the force necessary to knock off the corner fragments. Tetrahedroid fragments are therefore best developed in beds with little tendency to cleave along closely-spaced bedding planes, or whose bedding planes are quite widely spaced in relation to the joint spacing of the strata.

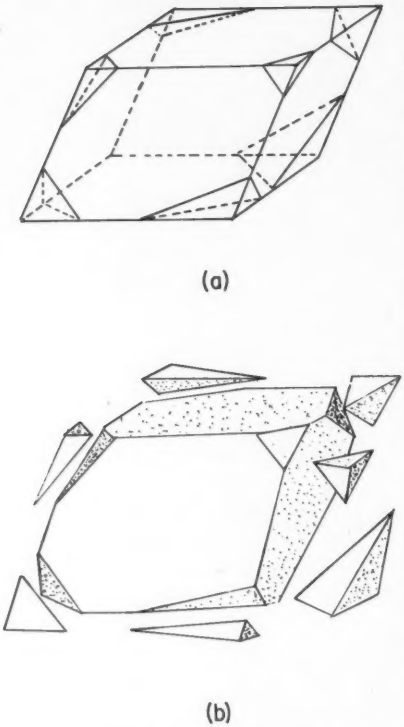

FIG. 4.—(a) rhombohedral joint block with various fracture planes shown, along which corners will break off. (b) same joint block with corner fragments of various shapes "exploded" away from block.

ENVIRONMENTAL SIGNIFICANCE

Field observations by the present writer indicate that tetrahedroid pebbles, particularly the sagittate shapes are extremely resistant to transportation by streams, save in high-velocity floods of short duration. The sagittate forms become extremely stable if their apices are oriented upstream, producing a streamlined body which offers little resistance to the flow of water. Conditions of extremely high velocity and severe turbulence are required to move such particles, and, when moved at all, they tend to roll over laterally across the channel rather than downstream. Although the equidimensional tetrahedroid is less stable and not so streamlined as the sagittate shape, nevertheless the downstream path taken by such a particle in high velocity stream flow is a tortuous one, involving as much lateral movement as downstream progress.

Thus it is evident that well-defined tetrahedroid pebbles, angular to subround, may be considered as remaining quite near to the source of the fragments, and may prove to be diagnostic of such non-marine sediments as stream-channel deposits, alluvial fans and cones, and in the shore gravels of lakes whose shorelines lie in close proximity to the piedmont zone in intermontane basin areas.

Tetrahedroid pebbles may be expected in glacial and glaciofluvatile deposits associated with valley glaciation in mountainous areas.

Under certain conditions, it is conceivable that well-rounded tetrahedroid pebbles could be found in marine beach gravels. Wentworth (1922) describes and illustrates by photograph the beach gravels at Nantasket Beach, Massachusetts. In studying carefully Wentworth's photograph, several pebbles were noted which appear to be rounded tetrahedroids. Nantasket Beach is a complex of tombolos tied together by sand bars. The tombolos are drumlin hills, and contain material derived from other parts of Massachusetts and which have undergone transportation by glacial ice, by streams, and to a certain extent by shore currents. The tetrahedroid pebbles which occur in the Nantasket Beach gravels are considered to be reworked from the original stream valleys into glacial deposits, and further reworked by the action of waves and littoral currents into the marine gravels in which they now occur.

It is also possible that, under such favorable conditions as a sea cliff with a well-developed subaerial wave-cut terrace or abrasion platform, cut into well-jointed rock as described above, joint

blocks might drop to the base of the platform and tetrahedroid corners broken off in the process. Wentworth (1922) illustrates such an abrasion platform cut into jointed trap of Triassic age at the entrance to New Haven Harbor near Fort Hale, Connecticut.

Although it has been suggested that, under certain conditions, marine shore gravels may be found to contain tetrahedroid pebbles, the writer believes that an abundance of well-defined and easily recognized tetrahedroid pebbles, subangular to sub-round, with sagittate shape predominating, strongly indicates the non-marine origin of the coarse-grained clastic sediments in which they are found.

Further studies are in progress on conglomerates from many areas, in order to further check the validity of the above conclusions concerning the environmental significance of the tetrahedroid pebble. Investigations are also being made of other distinctive pebble shapes associated with the tetrahedroid pebble, including the rhomboid and sphenoid pebbles commonly found in the stream gravels of the Central Wasatch Mountains.

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FIGS. 1–4, SEPTEMBER, 1953

SOME SURFACE FEATURES OF MARINE SEDIMENTS MADE BY ANIMALS[1]

K. O. EMERY
University of Southern California

ABSTRACT

Bottom living animals form small topographic features that may be very abundant where current and wave action is minor or absent and where sediments are deposited very slowly, as in most oceanic areas of several thousand feet depth.

Much has been written on the mechanical action of animals on beaches, mud-flats, and other shallow water sediments, but relatively little is known of their influence on deeper water sediments owing to the difficulty of observation. In shallow water waves and currents are generally able to wash away most of the minor features such as tracks, trails, burrows, and mounds within hours after they are formed. In water of moderate depth, however, these features may last for months until waves and currents set up by seasonal storms or rare disturbances destroy them, and in deep water it is even possible that the features can remain for many years until they are obliterated by the activities of other animals or become buried. This might be expressed in another way: that in shallow water inorganic agents are dominant in shaping the sediment surface, whereas in deep water animals may dominate, even though animals are less abundant per unit area in deep water than in shallow. The boundary between shallow and moderately deep water is considered here to be a few tens of feet and the boundary between moderately deep and deep water, a few hundreds of feet.

During the past few years many photographs of the sea floor off southern California and elsewhere have shown evidences of animal activities on bottom sediments (Shepard and Emery, 1946; Northrup, 1951). One of the most successful devices for exploring the deepest areas has been the benthograph, a large hollow steel sphere containing a stroboscopic light source and a 70-mm camera capable of making 325 exposures during a single lowering (Emery, 1952). Following the usual fate of most oceanographic equipment, this device was lost, probably under an overhanging ledge of rock at a depth of 2440 feet in July 1952. During its lifetime, however, a small collection of excellent photographs of the bottom was obtained, from which figures 1 to 4 were selected to illustrate some of the minor features formed by animals.

[1] Contribution of Allan Hancock Foundation No. 115.

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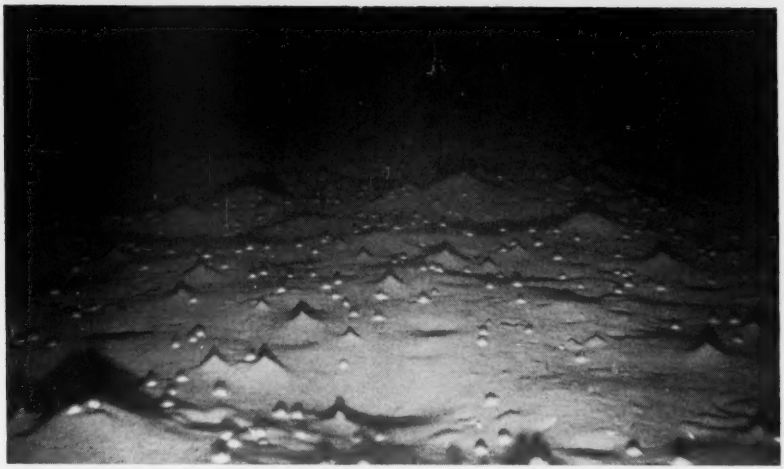

FIG. 1.—Insular shelf east of Santa Catalina Island at Lat. 33° 19.0′, Long. 118° 17.7′, 295 feet. September 22, 1951 (AHF 2057½). Bottom edge is about 6 feet wide. The sediment is a light green medium-grained foraminiferal glauconitic sand. The conical mounds and holes are the work of holothurians and worms. Trails in the lower left were made by sea urchins; other sea urchins are abundant throughout the area as oval white spots.

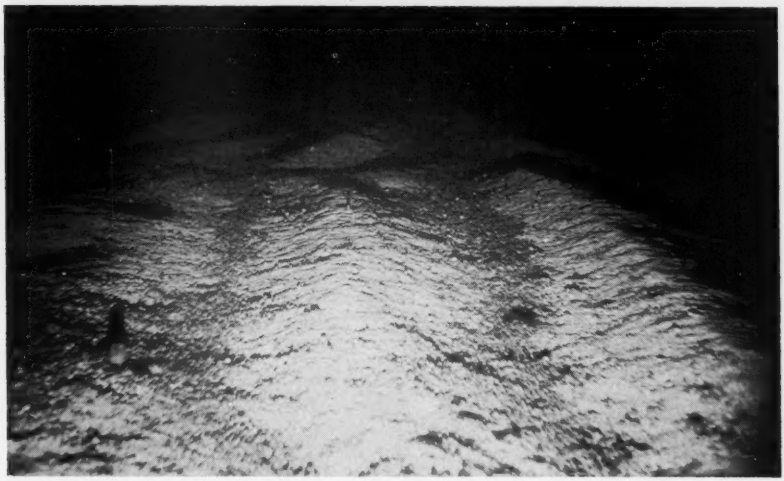

FIG. 2.—Top of Osborn Bank at Lat. 33° 22.0′, Long. 119° 02.9′, 190 feet. November 19, 1951 (AHF 2086). Bottom edge is about 6 feet wide. The sediment is a white very coarse-grained shell sand. Photograph was taken at the end of a summer of small waves. It shows large ripple marks probably made by the previous winter's storm waves and subsequently somewhat smoothed by burrowing animals probably chiefly worms.

FIG. 3.—Slope south of Palos Verdes Hills at Lat. 33° 41.2′, Long. 118° 20.2′, 870 feet. April 9, 1952 (AHF 2105). Bottom edge is about 6 feet wide. Camera is facing a 40° slope. The sediment is light green mud probably only a few inches thick and overlying shale. The abundant small animals, probably the anelid worm, Travisia, and the fish disturb the sediment, doubtlessly causing some of it to move down the slope as slow creep or perhaps as occasional thin mud slides.

FIG. 4.—Floor of Catalina Basin at Lat. 33° 22.2′, Long. 118° 47.9′, 4370 feet. April 29, 1951 (AHF 2111). Bottom edge is about 6 feet wide. The sediment is soft green mud. Scattered about the surface are worm tubes, brittle stars, holothurians, and probable comatulid crinoids. The bumpy surface is evidently the result of burrowing activities of all these animals.

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